NACA TN 3088

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3088

DETERMINATION OF THE FLYING QUALITIES OF THE DOUGLAS DC-3 AIRPLANE

By Arthur Assadourian and John A. Harper

Langley Aeronautical Laboratory
Langley Field, Va.

Washington
December 1953

1G

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3088

DETERMINATION OF THE FLYING QUALITIES OF THE DOUGLAS DC-3 AIRPLANE

By Arthur Assadourian and John A. Harper

SUMMARY

Flying qualities of the Douglas DC-3 airplane have been evaluated from a series of flight tests which were conducted to determine the longitudinal and lateral stability and control characteristics and stalling behavior of the airplane. Handling qualities are presented and compared with current Air Force—Navy handling-qualities specifications. Also included in the report for possible use by organizations using the DC-3 as a test vehicle for autopilots are some transient-response data from which some of the frequency-response characteristics of the airplane were determined.

Although the Douglas DC-3 airplane was designed before the formulation of any handling-qualities requirements, it satisfied most of the specifications for its type. Some of the characteristics which did not satisfy the requirements are as follows: The airplane was longitudinally unstable for certain conditions of airspeed and center-of-gravity position for the power-on configurations; the specified maximum elevator-control-force gradient in maneuvers in most cases was exceeded; the rudder forces required to overcome the adverse yaw in aileron rolls exceeded the allowable limit of 180 pounds; the rudder and aileron forces in steady sideslips tended to lighten at the higher angles of sideslip and the rudder forces actually reversed under some conditions. However, in spite of the few cases in which the airplane did not satisfy the requirements, the pilot thought that the airplane exhibited no serious flying-qualities deficiencies and handled well in normal flight.

INTRODUCTION

Although a large number of Douglas DC-3 airplanes have been built and widely used as transports for many years, only limited quantitative information is available on the stability and control characteristics of the airplane. Early tests of the stalling characteristics were conducted by the NACA and by the British, but reports on these tests are not generally available. Since the majority of transport pilots are familiar with the characteristics of this airplane, quantitative information on its handling qualities would serve as a basis for comparison with the handling qualities of present and future transports. It was therefore proposed to conduct a series of flight tests to determine the flying qualities of the DC-3.

Many versions of the DC-3 have been used in commercial and military applications. Variations which might affect the aerodynamic characteristics consisted principally of utilizing different engines and of making minor external changes. Since the basic design was the same for all models, it was considered that the handling qualities of the airplane used in the present study would be representative of the flying characteristics of all models.

It appeared reasonable to present the results of these flight tests in a form suitable for comparison with current Air Force—Navy handling-qualities specifications (ref. 1). However, it should be realized that the DC-3 was designed long before these requirements or the earlier NACA handling-qualities requirements were formulated. Any instances in which the handling qualities of the DC-3 do not meet the existing quantitative specifications should not be interpreted as a failure of the airplane to meet standards recognized at the time of its design. The outline of the handling-qualities requirements is used simply as a convenient and logical method of presenting the results. This method of presentation will aid in making comparisons with the test results of other airplanes.

In recent years, there has been widespread interest in automatic stabilization of airplanes in flight. Since several organizations have used the DC-3 as a test vehicle for autopilots, some sample data showing the longitudinal and lateral frequency-response characteristics have also been included in this report. Transient-response characteristics are also presented from which the frequency response can be obtained for other conditions.

DESCRIPTION OF AIRPLANE

The Douglas DC-3 is a twin-engine, low-wing transport airplane of all-metal, semimonocoque construction with fabric-covered control surfaces. Several photographs of the airplane (model C-47B) are shown in figure 1 and a three-view drawing with pertinent dimensions is presented in figure 2.

All the control surfaces were statically and aerodynamically balanced. The aerodynamic balance of the elevator and rudder was of the overhanging type, and that of the ailerons was of the Frise type. Trim tabs were provided on the rudder, both elevator surfaces, and the right aileron. Curves showing the variation of cockpit control positions with their corresponding control-surface positions under no-load conditions are presented in figure 3.

The friction in terms of control forces of the elevator, rudder, and aileron control systems was measured in a closed hangar at about 60° F. Since the autopilot servo pistons were connected directly into the control systems, the measured friction values included the friction produced by these piston assemblies. However, as shown in the following table, only the rudder friction exceeded the specified limits of reference 1:

Control	Friction at neutral deflection, lb	Maximum allowable friction at neutral deflection, lb
Elevator	±7.5	±8
Rudder	±18	±15
Aileron	±5	±6

The trailing-edge split flaps were constructed of metal and were hydraulically actuated. The landing gear was of the conventional tail-wheel type with a tail wheel that could swivel 360° or be locked in the trail position from the cockpit. The two main wheels were hydraulically retractable into the engine nacelles with only the bottoms of the wheels protruding whereas the tail wheel was of the fixed type.

General specifications of the airplane, obtained from reference 2, are presented in table I.

INSTRUMENTATION

Standard NACA instruments were used in the DC-3 airplane for the flight tests. The recording instruments were mounted approximately at the center of gravity and a 1/10-second timer synchronized all the records. Control positions were determined by electrical control-position recorders. The transmitting elements were mounted at the inboard bell-crank of each aileron and at the elevator and rudder horns. Control-surface angles were measured with respect to the fixed surfaces to which they were attached. No corrections were made for twist of the surfaces under load. Trim-tab measurements were made by reading the cockpit tab-position indicators, which were calibrated to give tab angles with respect to the control surfaces. Control forces were measured with strain-gage equipment located on the rudder pedals and control wheel. A sideslip transmitter, located at the end of a boom 1 chord ahead of the left wing tip, was used to record sideslip angle. The sideslip data were not corrected for angularity in the flow existing at the sideslip vane. Recording accelerometers were used to determine normal, transverse, and longitudinal accelerations. For pilot reference, an indicating normal accelerometer was mounted in the cockpit. Rolling, pitching, and yawing angular velocities were determined from their respective angular-velocity recorders. The angle of bank for steady flight conditions was obtained from the readings of a recording inclinometer. Free-air temperature was determined from weather reports and standard-atmosphere tables.

Airspeed was measured with a Kollsman type 651 airspeed head mounted at the end of a boom, 1 chord ahead of the right wing tip. The static and total pressures sensed by the Kollsman head were transmitted to a pressure recorder. The entire airspeed system was calibrated for position error by means of a trailing airspeed bomb. Calibrated airspeed as used herein corresponds to the reading of a standard A-N airspeed meter connected to a pitot-static system that is free from position error and is defined by the formula

$$V_c = 45.08f_o \sqrt{q_c}$$

where V_c is in miles per hour, q_c is the difference between total pressure and correct static pressure in inches of water, and f_o is the compressibility correction factor at sea level (ref. 3).

TEST RESULTS AND DISCUSSION

The service airspeed system consisted of a pair of pitot-static heads mounted under the fuselage below the pilot's compartment. The static-pressure lines from both heads were joined together and connected to both the pilot's and co-pilot's airspeed meters.

These heads are of a design which would be expected to experience errors in the static pressure due to sideslip. The location of the heads below the center line of the fuselage would be expected to increase further the errors due to sideslip, because the crossflow at this location is increased by the presence of the fuselage.

This system is subject to position errors which are shown in figure 4 for various configurations of the airplane in straight and laterally level flight. Also shown in figure 4 are curves which give the variation of calibrated airspeed with sideslip angle for values of indicated airspeed of 90 and 130 miles per hour. These data were obtained in steady sideslips during which the pilot held a constant indicated airspeed. The airspeed readings of the Kollsman head mounted on the wing-tip boom were corrected for errors due to sideslip angle as determined from a previous wind-tunnel calibration.

LONGITUDINAL STABILITY AND CONTROL CHARACTERISTICS

Dynamic Longitudinal Stability

Short-period longitudinal oscillations were investigated in the rated-power clean condition at 130 and 180 miles per hour for each of two center-of-gravity positions at an altitude of about 5,000 feet. For these tests, the elevator control was abruptly deflected from trim and released for both pull-ups and push-downs. In every case, oscillations of the elevator and normal acceleration were completely damped in less than one cycle.

Longitudinal frequency-response characteristics and transient-response data are presented in a subsequent section of this report.

Static Longitudinal Stability

The airplane's static longitudinal stability characteristics were determined at two center-of-gravity positions, approximately 13 and 25 percent mean aerodynamic chord with landing gear up. The rearward shift of the center of gravity due to lowering the landing gear was approximately 0.9 percent mean aerodynamic chord. The airplane's take-off weights were approximately 24,500 pounds for tests at the forward center of gravity and approximately 26,200 pounds for the rearward center of gravity. Fuel was consumed from the front tanks for the forward-center-of-gravity tests and from the rear tanks for the rearward-center-of-gravity tests, causing at most a rearward change of 0.3 percent mean aerodynamic chord and a forward change of 1.2 percent mean aerodynamic chord in the center-of-gravity position, respectively. In the presentation of the data, account has been taken of the effect of varying fuel load on weight and center-of-gravity position.

The following table gives the various configurations in which the airplane was tested at each of the two center-of-gravity positions and a list of the figures in which the data are presented:

Configuration	Power setting at 5,000 to 10,000 feet altitude	Position of				Approximate trim speed, V_i, mph	Figure
		Flaps	Landing gear	Cowl flaps	Oil cooler		
Normal rated power, clean	43 in. hg (or full throttle) 2550 rpm Automatic rich	Up	Up	Free to trail (approx. 1/3 open)	Open	120	5(a)
Cruise (power for level flight at V_i = 145 mph)	29 in. hg 1900 rpm Automatic lean	Up	Up	-----do------	Open	145 (speed for maximum range)	5(b)
Glide	Engines idling	Up	Up	-----do------	Open	115	5(c)
Power approach (power for level flight at 100 mph)	30 in. hg 2550 rpm Automatic rich	Down	Down	-----do------	Open	100	5(d)
Landing	Engines idling	Down	Down	-----do------	Open	90	5(e)

Figure 5 contains plots of the variation of elevator angle, elevator force, and sideslip angle with calibrated airspeed for straight and laterally level flight. The dashed-line portions of the curves at low airspeeds were obtained from continuous stall approaches made separately from the static-stability tests. Test points obtained from these stall approaches were omitted because the trim conditions were slightly different from those used in the static-stability tests, and the curves were shifted slightly to compensate for this effect.

From the data presented in figure 5, the degree of stick-fixed and stick-free stability of the airplane can be determined. The data were also used to estimate the neutral points of the airplane in the various flight conditions. Data on the neutral-point locations are not presented because in some cases they were located so far from the test center-of-gravity range that the locations could not be determined accurately. The neutral-point estimations were used, however, to determine the stability characteristics at the specified forward and rearward limits of the center-of-gravity range, 11 and 28 percent mean aerodynamic chord, respectively. These limits were only slightly beyond the test center-of-gravity locations.

A discussion of the static longitudinal stability characteristics of the DC-3 airplane follows:

Normal rated power, clean (fig. 5(a)).- In the normal-rated-power clean condition, the airplane was unstable, stick-fixed, below about 150 miles per hour, and unstable, stick-free, below the trim speed (120 miles per hour) with the center of gravity at 25.5 percent mean aerodynamic chord. With the center of gravity at its rearward limit, neutral-point data show that the airplane would be unstable, stick-fixed, throughout the speed range. The stick-fixed stability would be almost neutral, however, and the stick-free stability positive when the airplane is trimmed at speeds near the normal cruising speed (160 miles per hour) with the center of gravity at its rearward limit.

Cruise (fig. 5(b)).- The airplane in the cruise condition was stable, stick-fixed, throughout the speed range and stable, stick-free, above about 110 miles per hour with the center of gravity at 25.2 percent mean aerodynamic chord. Below 110 miles per hour, the airplane was unstable, stick-free, but the requirements were satisfied because only pull forces were required to lower the speed. Neutral-point data show that the airplane would be unstable, stick-fixed, below about 110 miles per hour with the center of gravity at its rearward limit.

Glide (fig. 5(c)).- In the glide condition, the airplane would be stable, stick-fixed, throughout the speed range and stable, stick-free, above approximately 105 miles per hour with the center of gravity at its rearward limit as determined from neutral-point data. The neutral stick-free stability below 105 miles per hour was satisfactory because pull forces were required.

Power approach (fig. 5(d)).- In the power-approach condition, the airplane was unstable, stick-fixed, and neutrally stable, stick-free, below the trim speed of 100 miles per hour with the center of gravity at 25.8 percent mean aerodynamic chord. The airplane would be unstable, stick-fixed, and slightly unstable, stick-free, at values of airspeed below about 115 miles per hour with the center of gravity at its rearward limit.

Landing (fig. 5(e)).- In the landing condition, the airplane would be stable, stick-fixed and stick-free, throughout the speed range with the center of gravity at its rearward limit. At the forward test center-of-gravity position, the elevator forces tended to lighten near the stall.

General.- By comparing figures 5(a) and 5(b) with figure 5(c), the destabilizing effect of power is readily apparent in the plots of elevator angle against calibrated airspeed. With power on, the lowering of flaps and landing gear (fig. 5(d)) had little effect on the stick-free stability but resulted in further loss of stick-fixed stability. With the engines idling, the stick-fixed stability was increased with the extension of gear and flaps (fig. 5(e)). The tendencies toward instability of the airplane at low speeds for the power-on configurations were not considered serious by the pilot because of the light stick forces involved.

The flight characteristics of the DC-3 at cruising speeds were considered very good by the pilot. After trimming the airplane for straight and level flight at the higher speeds, it was seldom necessary to provide corrective control to maintain the selected flight path under normal atmospheric disturbances.

The stall speeds indicated in figure 5 for the rearward center-of-gravity positions were somewhat higher than those at the forward positions, a characteristic contrary to normal expectations. However, this result can be explained by the fact that tests at the rearward center-of-gravity positions were made at gross weights on the order of 2000 pounds higher than those at the forward center-of-gravity positions.

The data for the variation of sideslip angle with airspeed, shown in figure 5, indicate approximately 1° right sideslip in high-speed flight for all conditions. Steady-sideslip data showed that this vane reading was obtained when the lateral acceleration, as measured by the pendulum inclinometer, was zero. Because slipstream effects would be small in high-speed flight, a condition of zero lateral acceleration would probably correspond closely to zero sideslip. This sideslip reading is therefore believed to be due to outflow at the location of the vane.

Longitudinal Control

Longitudinal control in accelerated flight.- The longitudinal stability and control characteristics in accelerated flight were investigated in right and left turns made in the normal-rated-power clean condition at an altitude of approximately 5000 feet. Spot records were obtained in steady turns at 100 and 180 miles per hour at various accelerations. Figure 6 presents curves of the variation of elevator control force with change in normal acceleration at each speed for two center-of-gravity positions, while figure 7 shows the variation of elevator angle with airplane normal-force coefficient in the turns.

Throughout the test range of normal-force coefficients and accelerations in right and left turns, the airplane was stable, stick-fixed and stick-free, for both forward and rearward center-of-gravity positions. In all cases, the maneuver points were well behind the rearward center-of-gravity limit. The maximum elevator-control-force gradient in maneuvers as stated in the requirements (60 pounds per g for this airplane using a load factor of 3) was exceeded in most cases, especially for small values of acceleration.

Longitudinal control in landing.- The landing requirements were investigated at both forward and rearward center-of-gravity positions. A time history of a typical three-point landing made with the center of gravity at 14.2 percent mean aerodynamic chord is presented in figure 8. It can be seen that the requirements were satisfied, but only marginally so, in that almost maximum elevator and about 50 pounds of elevator force were used to land. For normal operating conditions, the landing characteristics of the airplane are considered to be adequate, but for near-maximum gross weights and forward center-of-gravity positions, three-point landings would be difficult to make, especially in view of the high stick forces to be expected as a result of the high degree of stability in the landing configuration at landing speeds.

Longitudinal control in take-offs.- A time history of a typical take-off with flaps up is shown in figure 9 with the center of gravity at 26.5 percent mean aerodynamic chord. The requirement that it be possible to assume take-off attitude at 80 percent of the stalling speed for the landing condition would probably be satisfied at the rearward center-of-gravity limit. However, the requirement stating that elevator push forces must not exceed 35 pounds in the take-off run was not satisfied, inasmuch as forces on the order of 70 pounds were recorded for take-offs at both forward and rearward center-of-gravity positions.

Longitudinal trim control.- The variation with speed of the power of the elevator trimming tabs in terms of control force per degree of tab deflection is presented in figure 10 for the normal-rated-power clean, glide, and landing configurations. The requirements for the longitudinal trim control were satisfied except for the airplane in the gliding condition in which case the required minimum trim speed of about 100 miles per hour could not be reached for the forward center-of-gravity positions. The indicated minimum trim speeds were about 82 and 115 miles per hour with the center of gravity at about 25 and 13 percent mean aerodynamic chord, respectively.

Longitudinal trim changes.- The requirements state that with the airplane trimmed at any given speed using any combination of engine power and flap and gear setting, it shall be possible to maintain the given speed without exerting push or pull forces greater than 50 pounds when the power, flap, and gear settings are varied in any manner whatsoever. This requirement was investigated in the present case by trimming the airplane at the indicated airspeeds, flap and gear settings, and engine power settings listed in the following table and making a change as indicated in the variable column. An inspection of the corresponding forces so determined shows that the requirement is satisfied. A desirable feature to be noted is that cutting the power at 90 miles per hour with the flaps and gear down (line 4 of the table) requires a pull force.

Indicated airspeed, mph	Position of		Power setting	Elevator tab setting for trim, deg, nose up	Variable	Elevator control force, lb
	Flaps	Landing gear				
100	Up	Up	50 percent normal rated 22 in. hg at 2500 rpm	6.5	Gear down	3 push
100	Up	Down	------do------	6.5	Flaps down	4 pull
100	Down	Down	------do------	6.5	Idle power	9.5 pull
90	Down	Down	------do------	---	Idle power	6.7 pull
90	Down	Down	Engines idling	12	Take-off power	15.3 push
90	Down	Down	Take-off power 48 in. hg at 2700 rpm	9	Gear up	2 push
90	Down	Up	------do------	9	Flaps up	29 push

Pitching Moment Due to Sideslip

The increment of elevator control force necessary to counteract the pitching moment due to sideslip produced by 50 pounds of rudder force at the trim speeds of all the configurations tested was in every case less than 10 pounds. Also, in general, an increasing pull force was required with increasing sideslip.

Longitudinal Frequency Response

In order to obtain data on the longitudinal frequency-response characteristics of the DC-3, several approximate step elevator deflections were made in the normal-rated-power clean condition at indicated airspeeds of 100 and 180 miles per hour with the center of gravity at 12.5 percent mean aerodynamic chord. Typical transient-response data are presented in figure 11 for pull-ups to various values of normal acceleration. The time history of figure 11(d) was used to determine the frequency response of pitching velocity to elevator angle $\dot{\theta}/\delta_e$ of the DC-3 by means of the Fourier transform method and the result is shown in figure 12. A description of this method is available in reference 4.

LATERAL AND DIRECTIONAL STABILITY AND CONTROL CHARACTERISTICS

Dynamic Lateral and Directional Stability

The dynamic lateral and directional stability characteristics of the airplane were investigated in the cruising condition at indicated airspeeds of 170 and 120 miles per hour. For these tests, the rudder was abruptly deflected and released, right and left, and the ailerons were abruptly deflected and released, right and left. Typical time histories of rudder kicks are presented in figure 13. In all cases, the resulting oscillations were satisfactorily damped, the time required to damp to one-half amplitude being on the order of one cycle. There was no tendency for undamped, small-amplitude oscillations to persist, and both rudder and ailerons returned to their trim positions after release with no tendency for short-period oscillations.

Lateral and directional frequency-response characteristics obtained from transient-response data are presented in a subsequent section of this report.

Static Lateral and Directional Stability

Sideslip due to aileron deflection and rudder deflection required to overcome adverse aileron yaw.- An attempt was made to measure the adverse yaw due to aileron deflection with rudder fixed and the amount of rudder deflection required to overcome this adverse yaw in rolls out of 30° banked turns at 100 miles per hour in the clean and power-approach configurations. Typical time histories of these maneuvers are presented in figure 14. Rudder-fixed roll-outs in which the pilot held the rudder pedals fixed in the positions required for the initial steady turn are presented in the left-hand plots of figures 14(a) and 14(b). During these maneuvers, the rudder moved from its trim position so as to oppose the roll-out, that is, to increase the adverse yaw, notwithstanding the fact that the pedals were held fixed. This rudder movement was due to the strong tendency of the rudder to float with the wind, coupled with stretch in the rudder control system. The pilot's efforts to use the rudder to maintain zero sideslip during the roll-out are indicated in the right-hand plots of figures 14(a) and 14(b). As can be seen, the pilot was unable to move the rudder more than a few degrees in the direction necessary to counteract the adverse yaw even with pedal forces of about 150 pounds. In fact, he was quite unaware that the rudder moved only a fraction of the amount which he would expect from the amount of rudder pedal movement that he applied.

From maneuvers similar to those shown in figure 14, the data of figure 15 were obtained. This figure shows the maximum change in sideslip angle with change in total aileron angle for several roll-outs with the rudder pedals held fixed, or used in an effort to maintain zero sideslip. The angles of sideslip developed in the rudder-fixed rolls never exceeded 20° and therefore satisfied the requirements. However, the strong floating tendency of the rudder prevented the pilot from decreasing the adverse aileron yaw by more than a few degrees when using the rudder for that purpose. Decreasing the adverse yaw any further would entail rudder forces well beyond a pilot's capabilities. (The requirements specify 180 pounds as the allowable limit.) The inability of the rudder to overcome the adverse yaw developed in rolls out of turns and the high rudder forces involved did not satisfy the requirements. These characteristics would make coordinated turns at low airspeeds difficult, if not impossible, to make, but the pilot felt that the slipping and skidding involved in making turns with this airplane were not objectionable.

The rudder hinge-moment derivatives $C_{h_{\alpha}}$ and $C_{h_{\delta}}$ were estimated from data similar to that of figure 14. The values of the rate of change of rudder hinge-moment coefficient with angle of attack $C_{h_{\alpha}}$ and with rudder deflection C_{h_δ} were approximately -0.0030 and -0.0040 per degree, respectively. However, the value of C_{h_α} decreased to approximately zero for small ($\pm 3^\circ$) angles of sideslip, a type of variation that is to be expected with low-aspect-ratio surfaces. It can be seen, therefore, that the large pedal forces due to sideslip do not result from any abnormal hinge-moment characteristics of the rudder, but merely from the large area and chord of this surface.

Sideslip characteristics.- The sideslip characteristics of the airplane were investigated in straight, steady sideslips for various configurations at several indicated airspeeds. Records were taken of the aileron, elevator, and rudder control deflections and forces, the angle of bank, and the angle of sideslip. The results of these sideslips are presented in figures 16 to 20.

Directional stability: The control-fixed static directional stability as shown by the variation of rudder deflection with sideslip angle was positive for all configurations tested. The sideslip angle was always substantially proportional to the rudder deflection and therefore the requirements were satisfied.

The control-free static directional stability as shown by the variation of rudder force with sideslip angle was satisfactory for small angles of sideslip. However, the rudder force lightened for all configurations at the higher angles of sideslip, and in some cases the force approached zero (figs. 16(a), 17(a), and 18). In fact, force reversal (rudder overbalance or lock) was noted by the pilot on runs corresponding to figures 16(a), 17(a), 18, and 19(a) but the forces could not be measured as the rudder pedal was against its stop. This tendency towards force reversal and the corresponding lack of proportionality between rudder force and sideslip angle at the higher angles of sideslip did not satisfy the requirements.

Dihedral effect: The control-fixed dihedral effect as evidenced by the slope of the curve of total aileron angle with sideslip angle was positive in all conditions at all speeds. The airplane had a geometric dihedral angle of 5° outboard of the nacelles, and in the gliding condition, the effective dihedral was about 6.3°. This value dropped somewhat to about 5.9° for the normal-rated-power, cruising, and landing configurations and was still less (4.4°) for the power-approach condition. For the clean, power-on conditions, the effective dihedral decreased somewhat at the higher angles of sideslip but never approached zero.

The control-free dihedral effect as shown by the variation of aileron force with sideslip angle was positive for angles of sideslip between $\pm 10^\circ$ for all the configurations tested. However, at the higher sideslip angles, the forces lightened, but did not reverse. (See figs. 17(a) and 20(a).) This force-lightening tendency was not considered serious because the sideslip angles were high or the aileron forces were small.

Pitching moment due to sideslip: This subject was discussed previously and it was found that the requirements were easily satisfied. However, it might be pointed out that, since the pilot maintained constant indicated airspeeds while performing the steady sideslips, the calibrated airspeed decreased with increasing sideslip. This, in part, explains the fact that increasing up-elevator angle is required with increasing sideslip angle, especially at the lower airspeeds.

Side-force characteristics: The side-force characteristics of the airplane were found to satisfy the requirements as shown by the positive variation of the angle of bank with sideslip angle for all the conditions tested.

Lateral and Directional Control

Directional trim characteristics.- The directional trim characteristics were investigated in straight and laterally level flight. The requirement that the rudder control shall give sufficient directional control to trim the airplane in steady level flight at all speeds and in all conditions was satisfied.

Rudder control in take-off and landing.- The rudder control was adequate for normal take-offs and landings (figs. 8 and 9) and the rudder forces were reasonable. No take-offs or landings were made in a 90° cross wind, but it is considered that the rudder control would be sufficient to satisfy the requirements.

Rudder deflection required to overcome adverse aileron yaw.- The ability of the rudder to overcome the yawing moment due to full aileron deflection with a control-force increment of less than 180 pounds was discussed previously and was found to be inadequate.

Single-engine operation.- The following tests were made to determine the handling characteristics with one engine inoperative:

Uncontrolled attitude changes with asymmetric power: A test was made to determine the time it would take to reach a dangerous attitude if no corrective control were applied upon the complete loss of power of the right engine. (Propeller windmilling and in low pitch). Time histories of this maneuver with and without corrective control are presented in figure 21 for the airplane initially in the take-off configuration: gear down, flaps up, and full take-off power. About 8 seconds were required to reach a dangerous attitude with no correction and the controls held fixed. Calculations showed that the angle of bank, not presented in the figure, reached a value of approximately 54° before recovery was started. It is felt that 8 seconds provides adequate time for the pilot to cope with the emergency and be able to recover. Figure 21(b) shows the same maneuver with corrective control applied immediately to keep the airplane flying straight and laterally level.

Directional and lateral control power: A series of tests were made with one engine inoperative to determine the minimum speed at which the airplane could still be flown with zero sideslip and bank. With the airplane trimmed in the take-off configuration at an indicated airspeed of 90 miles per hour, the pilot cut the right engine at an airspeed of 110 miles per hour. He was then able to decrease the airspeed to 90 miles per hour while maintaining zero sideslip. Therefore, it is believed that the requirement that the rudder be capable of holding the airplane with zero yawing velocity and not more than 5° of bank at all speeds above 85 miles per hour in that configuration was satisfied.

In the above series of asymmetric-power tests, the low (13 pounds) value of aileron force required to balance the airplane easily satisfied the requirements, whereas the rudder force required was marginal (180 pounds).

Directional and lateral trim characteristics: In order to determine the power of the rudder trim tab under asymmetric power conditions, the airplane was trimmed in the take-off configuration at a calibrated airspeed of 97 miles per hour. With the right engine cut, it was found that the trim tab could reduce the rudder pedal forces to zero for a calibrated airspeed as low as about 100 miles per hour in wings-level straight flight. At the same time, about half the available aileron trim tab was used to reduce the aileron forces to zero. Therefore, the rudder and aileron trim-tab requirements for single-engine operation were considered to be satisfied.

The requirement that the airplane with rudder free may be balanced directionally in steady straight flight by sideslipping and banking with one engine inoperative in the clean configuration was not investigated. However, from the data determined in previous tests, it is felt that by slipping and banking, the airplane can be flown with the rudder free for a calibrated airspeed as low as 110 miles per hour, thus satisfying the requirement.

Power of rudder and aileron trimming tabs.- The lateral and directional trim tabs were sufficiently powerful to trim the control forces to zero throughout the speed ranges in steady straight flight with both engines operating. The trim-tab requirements were easily met.

Rolling moment due to sideslip.- The time histories of typical rolls out of turns presented in figure 14 show that the adverse yaw never caused the rolling velocity to reverse, and thus the requirements were satisfied.

Aileron control characteristics.- The aileron control characteristics were investigated in abrupt rudder-pedal-fixed aileron rolls at various speeds with the airplane in the normal-rated-power clean and landing configurations. Typical time histories of the rolls with the airplane in the clean condition are presented in figure 22.

The aileron control characteristics of the airplane may be summarized as follows:

(a) The variation of the angle of bank with time immediately following an abrupt aileron deflection was always in the correct direction.

(b) The peak value of rolling acceleration never occurred later than 0.3 second after full aileron deflection was reached in the rudder-fixed rolls tested.

(c) The variation of maximum rolling velocity with change in total aileron angle obtained in abrupt aileron rolls for various conditions is presented in figure 23. It can be seen that the maximum rolling velocity varied smoothly with and was approximately proportional to the aileron deflection.

(d) The aileron-effectiveness parameter $pb/2V$ and the aileron-force variations with change in total aileron angle are shown in figure 24 for various conditions. The minimum acceptable peak rolling rate of 0.07 was easily obtained for the conditions specified in the requirements. It should be noted that, even though the pilot used full wheel throw, full available aileron angle is not obtained because of stretch in the control cables. As the airspeed increases, less aileron angle is obtained. As shown in figure 3, the maximum wheel throw was 180°. Therefore, the requirement that the wheel throw should not exceed 120° to obtain the required rate of roll was not satisfied.

The aileron control force varied smoothly with aileron deflection and there was no tendency for the ailerons to shake, snatch, or overbalance for all the conditions tested. In the normal-rated-power clean configuration (fig. 24(a)), the aileron control force required to obtain a $pb/2V$ of 0.07 was only slightly more than the allowable of 80 pounds for airspeeds above about 160 miles per hour.

Lateral and Directional Frequency Response

In order to obtain data on the lateral frequency response characteristics of the DC-3, several step aileron deflections were made in the normal-rated-power clean condition at various speeds. Typical transient-response data are presented in figure 22 for right and left rolls. The lateral frequency response of rolling velocity to aileron angle $\dot{\phi}/\delta_{a_T}$

of the DC-3, as determined by the Fourier transform method, is presented in figure 25. A description of this method is available in reference 4.

Similarly, several rudder kicks were performed in the normal-rated-power clean condition at various airspeeds to determine the directional frequency response. Typical transient-response data are presented in figure 13 for left rudder kicks at two airspeeds. The time history of figure 13(b) was used to determine the frequency response of yawing velocity to rudder angle $\dot{\psi}/\delta_r$ and the results, as obtained by means of the Fourier transform method, are shown in figure 26.

STALLING CHARACTERISTICS

Typical time histories of stall approaches and stalls in straight and level flight of the Douglas DC-3 airplane in various configurations are presented in figure 27. For the power-on conditions, the left wing dropped abruptly and the nose fell at the stall, whereas with the engines idling, there seemed to be little tendency for the airplane to roll and the nose pitched down slowly. Isolated cases of aileron snatch were noted by the pilot (fig. 27(b)). For all conditions, normal stall recovery procedure was used to regain control of the airplane. No tests were made to determine the loss of altitude before recovery was completed, but for the power-on stalls with the airplane rolling abruptly, considerable altitude was required before control could be regained.

The pilot considered that there was adequate stall warning provided by airframe buffeting which he could detect at speeds well above the stalling speed for all configurations and power conditions tested. The buffeting increased in intensity as the stall was approached, and was considered very severe in the power-off conditions. The buffeting is not very apparent in the instrument records, except for some indication during the stall in the power-off conditions (figs. 27(c) and (e)). Probably the buffeting was of such frequency that it could not be measured by these instruments.

The conclusion with regard to stall warning in the present tests is at variance with that stated in previous unpublished tests by the NACA. These tests were conducted in 1937 with an earlier model of the DC-3 which had less powerful engines and different engine cowlings, but which was otherwise similar to the airplane used in the present tests. The conclusion of the earlier tests was that the stalling characteristics in the power-on condition were dangerous because of lack of adequate stall warning. While an actual difference in characteristics may result from the slight change in configuration, it is considered more likely that this difference of opinion over a span of years is caused by the manner in which test pilots evaluate the stalling characteristics of a particular airplane in terms of the many different types with which they are familiar. At the present time, test pilots are accustomed to flying high-speed aircraft which frequently have marginal stability and stalling characteristics; whereas, at the time the DC-3 was first introduced, pilots were familiar with biplanes which generally had good stability and stalling characteristics. Aside from the difference of opinion with regard to stall warning, the results of the two sets of tests are in good agreement. Both sets of results show very little change in elevator angle or force during power-on stall approaches due to the small degree of longitudinal stability, especially at the rearward center-of-gravity location. This lack of control "feel" was not considered too objectionable by the pilot in the present tests, but was a major criticism of the pilots conducting similar studies in 1937.

CONCLUSIONS

Even though the Douglas DC-3 airplane was designed and built prior to the formulation of any of the quantitative handling-qualities requirements, the flight characteristics satisfied most of the specifications, and thus the airplane compares favorably with more recent airplanes of its type. However, some of the more important flight characteristics which did not satisfy the current Air Force—Navy handling-qualities specifications should be mentioned and are as follows:

1. In the normal-rated-power clean configuration, the airplane would be unstable, stick-fixed, throughout the speed range and unstable, stick-free, below the trim speed (120 miles per hour) with the center of gravity at its rearward limit (28 percent mean aerodynamic chord); however, when trimmed at speeds near the normal cruising speed (160 miles per hour), the stick-fixed stability would be almost neutral.

2. The airplane in the power-approach condition would be unstable, stick-fixed and slightly unstable, stick-free, at values of airspeed below about 115 miles per hour with the center of gravity at its rearward limit.

3. The specified maximum elevator control-force gradient in maneuvers (60 pounds per g) was exceeded in most cases, especially at small values of acceleration.

4. The rudder forces required to overcome the adverse aileron yaw developed in rolls out of turns exceeded the allowable limit of 180 pounds. Because of the high rudder forces, the pilot was unable to deflect the rudder enough to overcome the adverse yaw with large aileron deflections.

5. The rudder and aileron forces in steady sideslips tended to lighten for angles of sideslip larger than about 10°. A few cases of rudder overbalance were also noted by the pilot at the higher angles of sideslip.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 29, 1953.

REFERENCES

1. Anon.: Specification for Flying Qualities of Piloted Airplanes. NAVAER SR-119B, Bur. Aero., June 1, 1948.

Anon.: Flying Qualities of Piloted Airplanes. USAF Spec. No. 1815-B, June 1, 1948.

2. Anon.: Handbook - Flight Operating Instructions. USAF Series C-47, C-47A; Navy Models R4D-1, R4D-5; Aircraft. AN 01-40NC-1, U.S. Air Force and Bur. Aero., Nov. 20, 1944. (Revised Nov. 2, 1951.)

Anon.: Handbook - Erection and Maintenance Instructions. USAF Series C-47, C-47A, C-47B, C-47D; Navy Models R4D-1, R4D-5, R4D-6, R4D-7; Aircraft. AN 01-40NC-2, U.S. Air Force and Bur. Aero., Oct. 15, 1944. (Revised May 5, 1952.)

3. Aiken, William S., Jr.: Standard Nomenclature for Airspeeds With Tables and Charts for Use in Calculation of Airspeed. NACA Rep. 837, 1946. (Supersedes NACA TN 1120.)

4. LaVerne, Melvin E., and Boksenbom, Aaron S.: Frequency Response of Linear Systems From Transient Data. NACA Rep. 977, 1950. (Supersedes NACA TN 1935.)

TABLE I

GENERAL SPECIFICATIONS OF THE AIRPLANE

Make and designation	Douglas DC-3 (Model C-47B)
Engines (two)	Pratt and Whitney R-1830-90C Twin Wasp
Power ratings:	
Take off and military (1200 bhp), each	2700 rpm at 48 in. Hg at sea level (automatic rich)
Maximum continuous	2550 rpm at 43 in. Hg or full throttle (automatic rich)
Propellers (two)	Hamilton standard 3-bladed hydromatic quick-feathering with constant-speed control
Hub number	Hamilton 23E50
Blade number	6477 A-0 (wide)
Blade angle setting, deg	88 high; 16 low
Diameter, ft	11.58
Reduction-gear ratio	16:9
Fuel capacity, gal:	
Main tanks (front) (two), each	202
Auxiliary tanks (rear) (two), each	200
Oil capacity, gal:	
Nacelle tanks (two), each	29
Permissible center-of-gravity range, percent M.A.C.	11 to 28
Gross weights, lb:	
Design	26,000
Maximum (limited by single-engine operation)	33,000
Recommended (for normal operation)	29,000
Maximum weight for present tests:	
Forward center of gravity	24,700
Rearward center of gravity	26,600
Load factors:	
Design limit	3.00
Maximum-gross-weight limit	2.33
Landing (at max. gross weight)	2.95

TABLE I.- Continued

GENERAL SPECIFICATIONS OF THE AIRPLANE

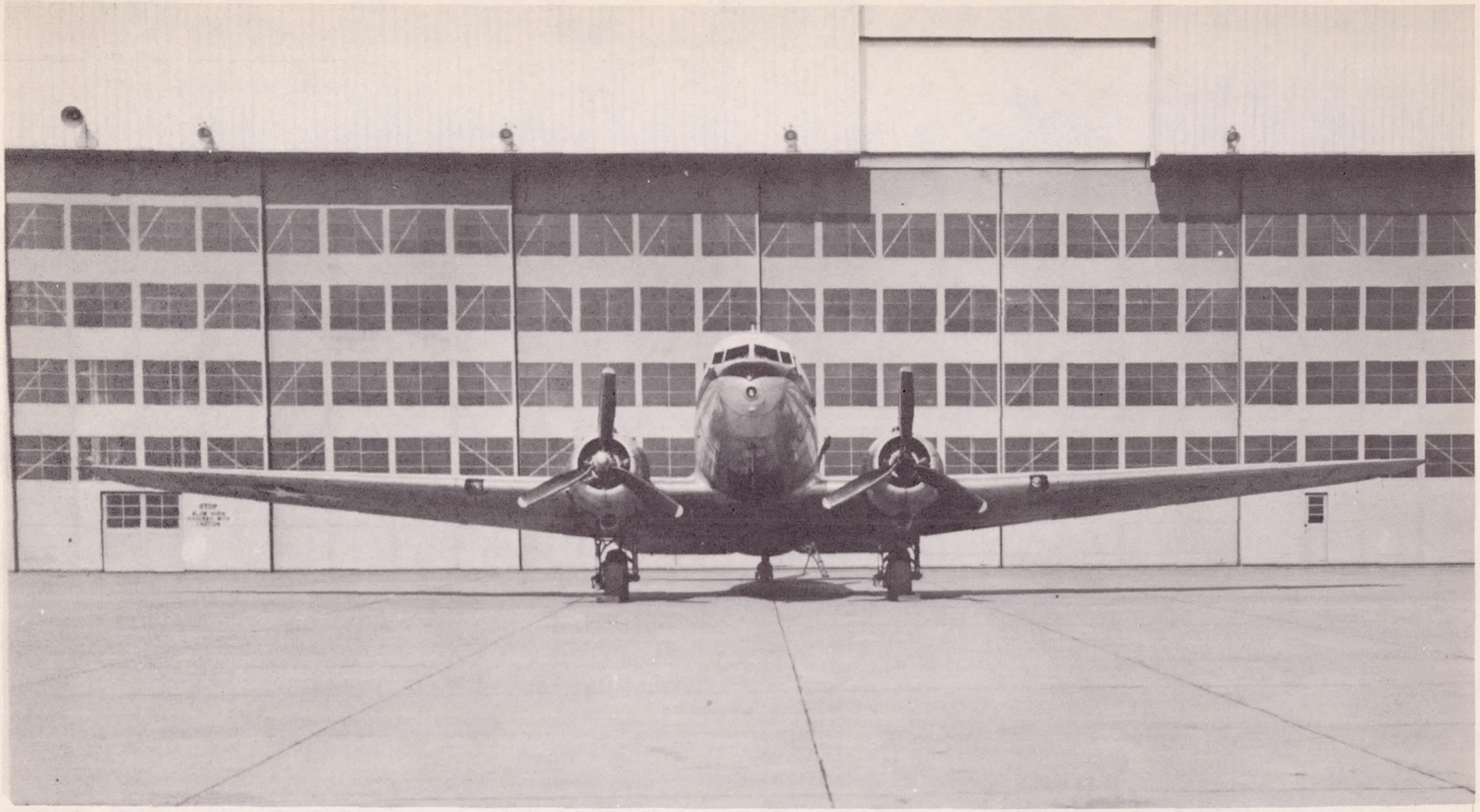
Wings:	
Area, sq ft	988.9
Span, ft	95
Aspect ratio	9.13
Airfoil section, root	NACA 2215
Airfoil section, tip	NACA 2206
Mean aerodynamic chord, in.	138.1
Longitudinal distance from leading edge of root chord to leading edge of mean aerodynamic chord, in.	31.9
Root chord, in.	170
Tip chord (30 in. inboard of actual tip), in.	56
Incidence, deg	2
Dihedral (measured at tip of front beam), deg	5
Sweepback (outer wing panel), deg	15.5
Wing flaps (split, trailing edge):	
Area, total, sq ft	82
Span, in.	499
Deflection, maximum down, deg	45
Ailerons (Frise):	
Area, total, sq ft	104.7
Length, each, in.	291
Trimming-tab area (right aileron), sq ft	1.91
Trimming-tab deflection range, (deg from aileron)	12.3 right wing up 11.9 right wing down
Horizontal tail:	
Area, total, sq ft	179.2
Span, in.	320
Elevator area, total (including tabs), sq ft	83.4
Elevator trimming-tab area, total, sq ft	3.6
Elevator trimming-tab deflection range (deg from elevator)	11.4 nose up to 10.2 nose down
Dihedral, deg	0
Incidence, deg	0

TABLE I.- Concluded

GENERAL SPECIFICATIONS OF THE AIRPLANE

Vertical tail:

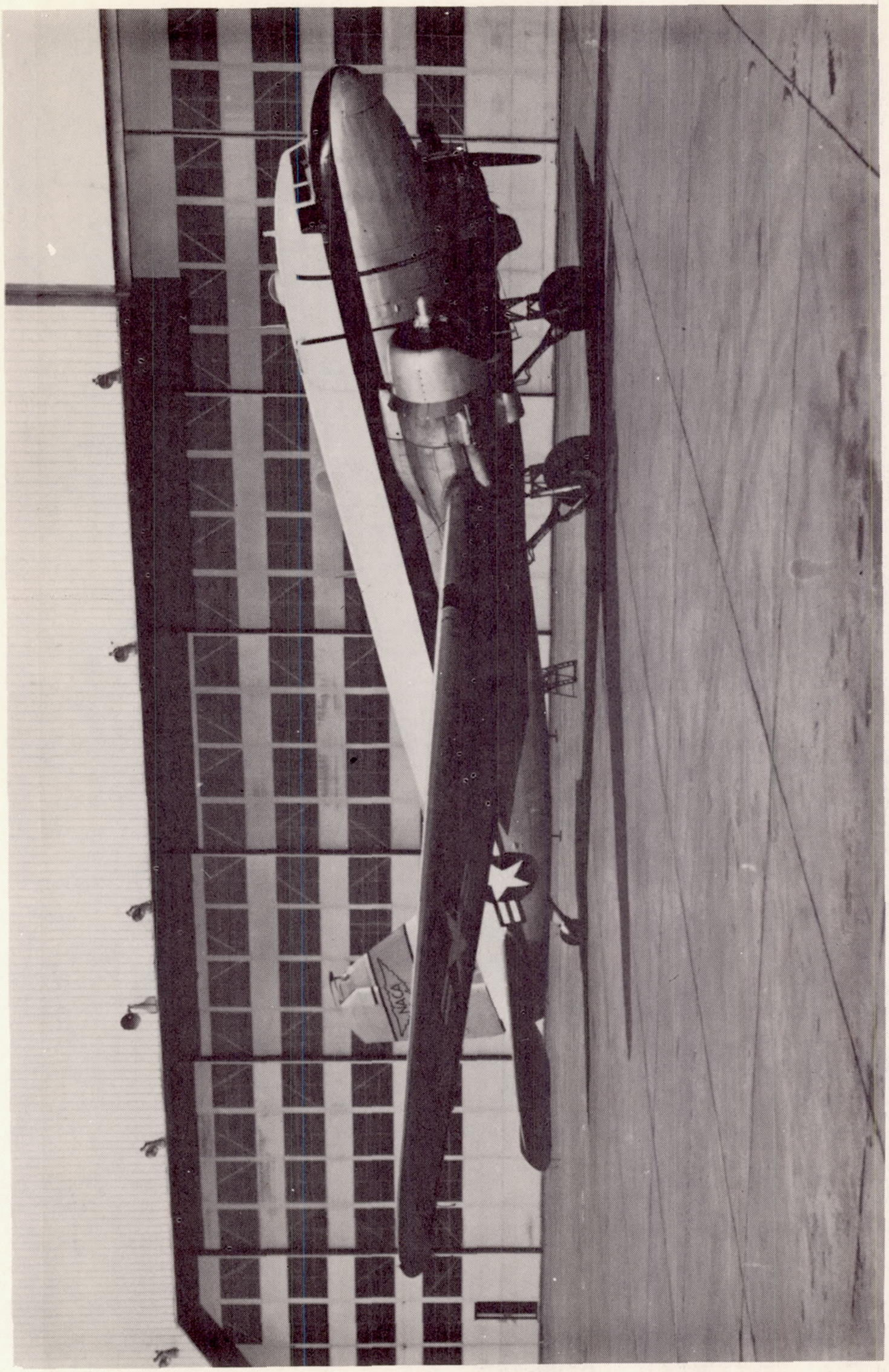
Area, total, sq ft	84.5
Offset from thrust axis, deg	0
Rudder area, including tab, sq ft	46.6
Rudder trimming-tab area, sq ft	3.0
Rudder trimming-tab deflection range (deg from rudder)	12.5 nose right to 12.2 nose left



L-77641

(a) Front view.

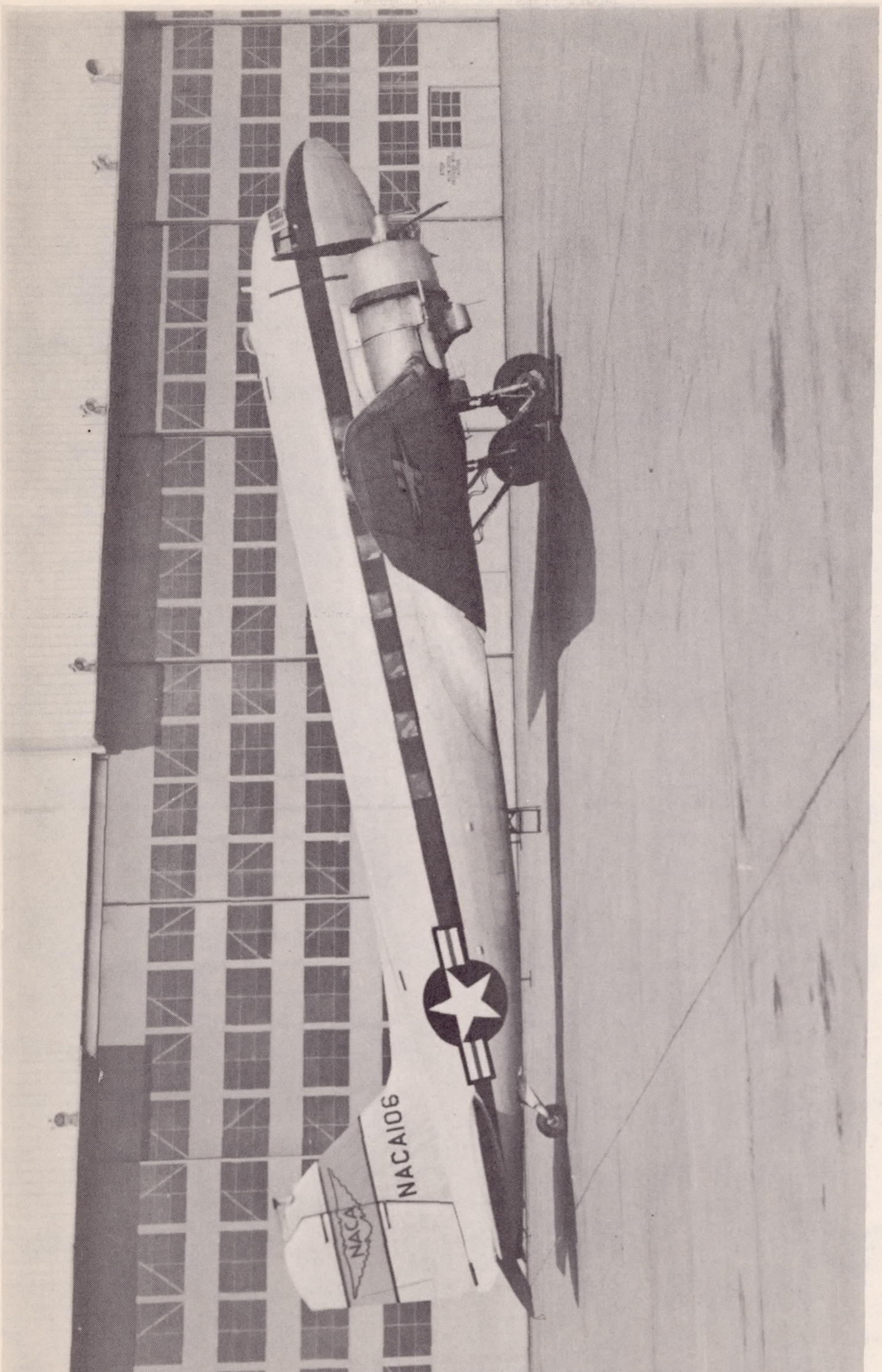
Figure 1.- Photographs of the Douglas DC-3 (model C-47B) airplane.



L-77642

(b) Three-quarter front view.

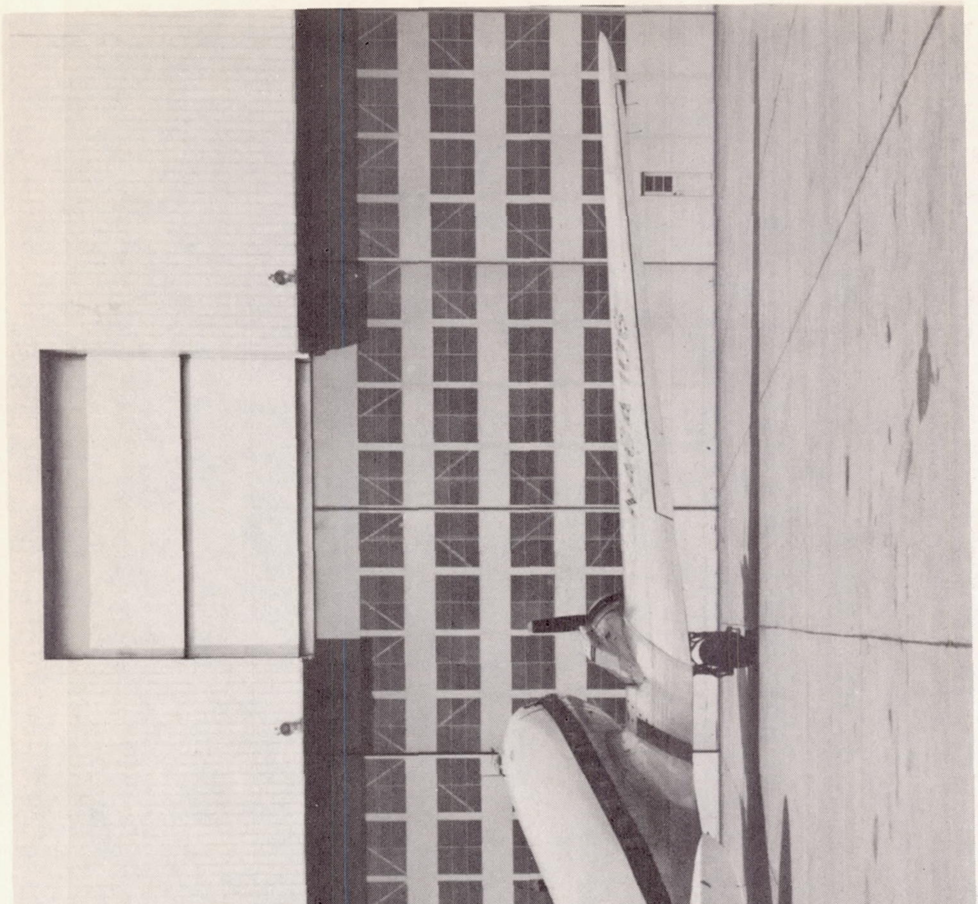
Figure 1.- Continued.



L-77643

(c) Side view.

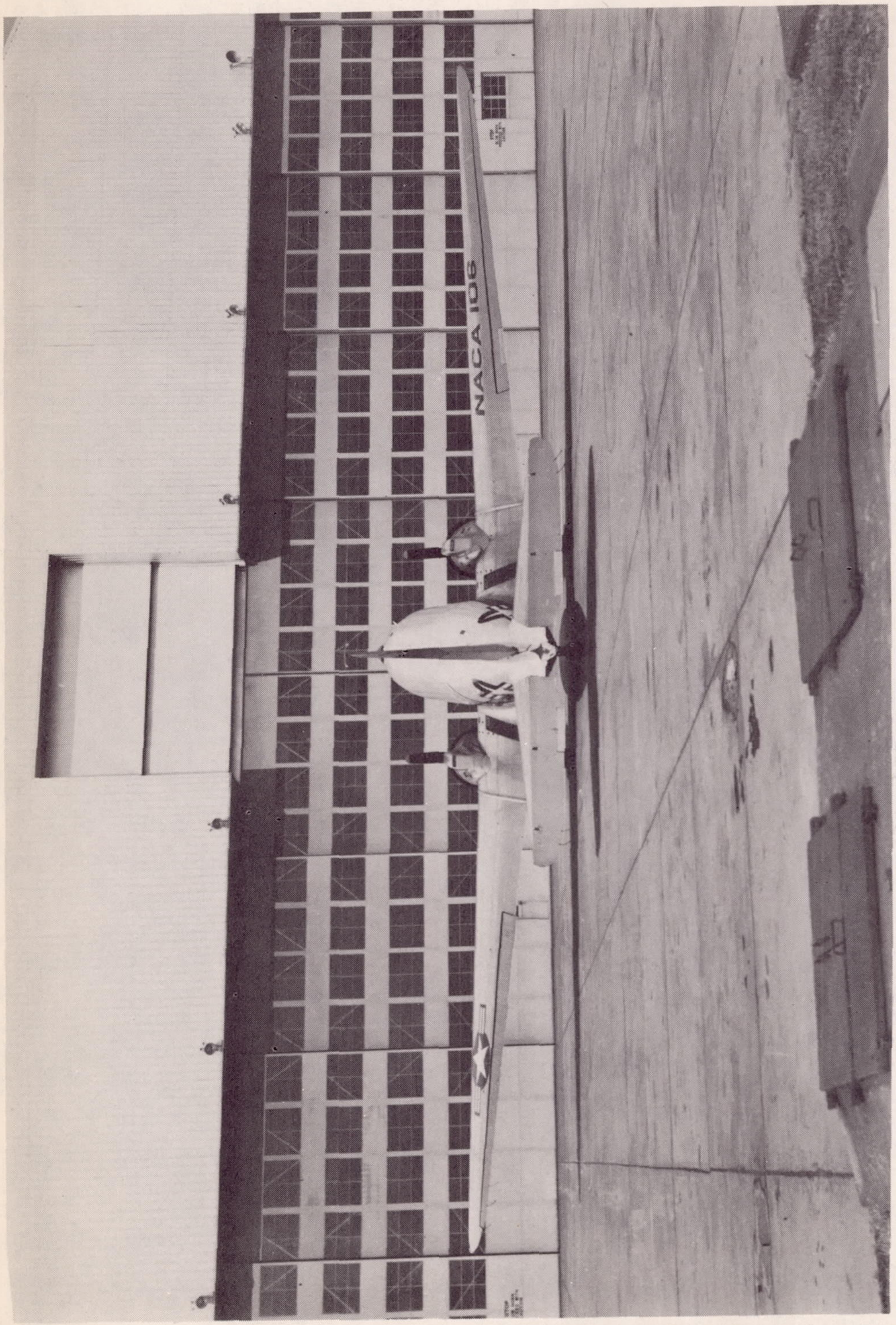
Figure 1.- Continued.



L-77644

(d) Three-quarter rear view.

Figure 1.- Continued.



L-77645

(e) Rear view.

Figure 1.- Concluded.

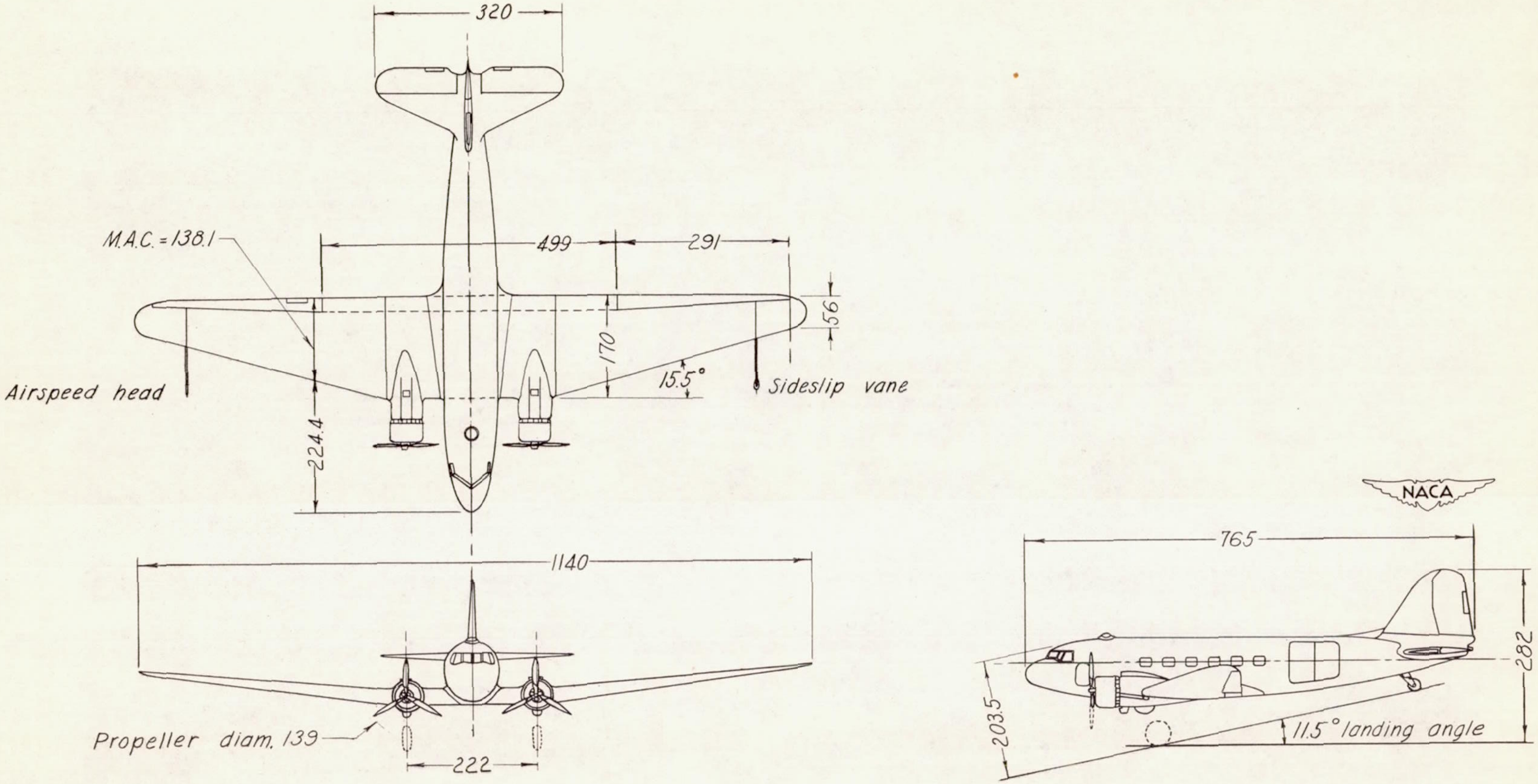


Figure 2.- Three-view drawing of a Douglas DC-3 model C-47B. All dimensions in inches.

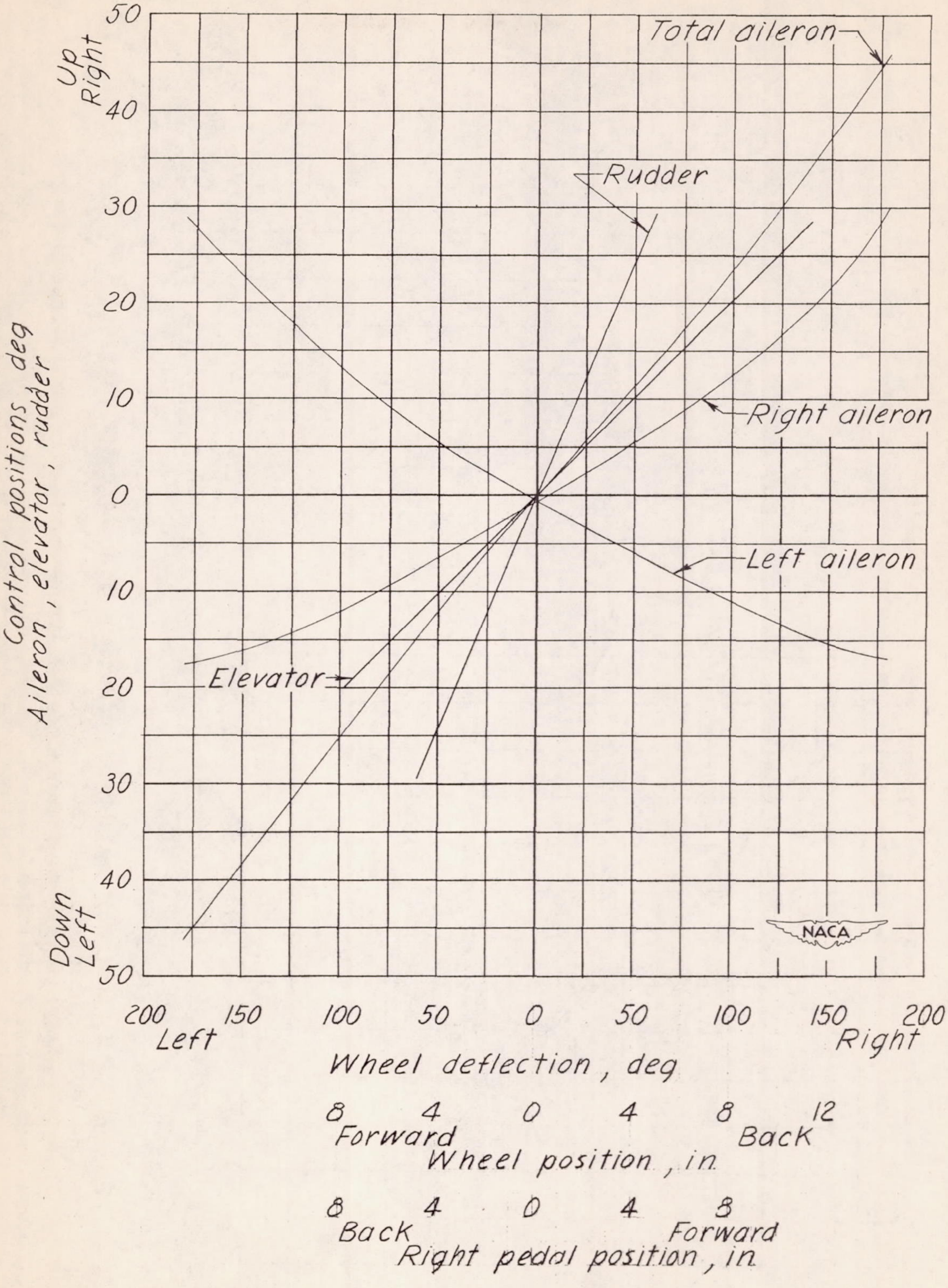


Figure 3.- Variation of aileron elevator and rudder positions with cockpit control positions.

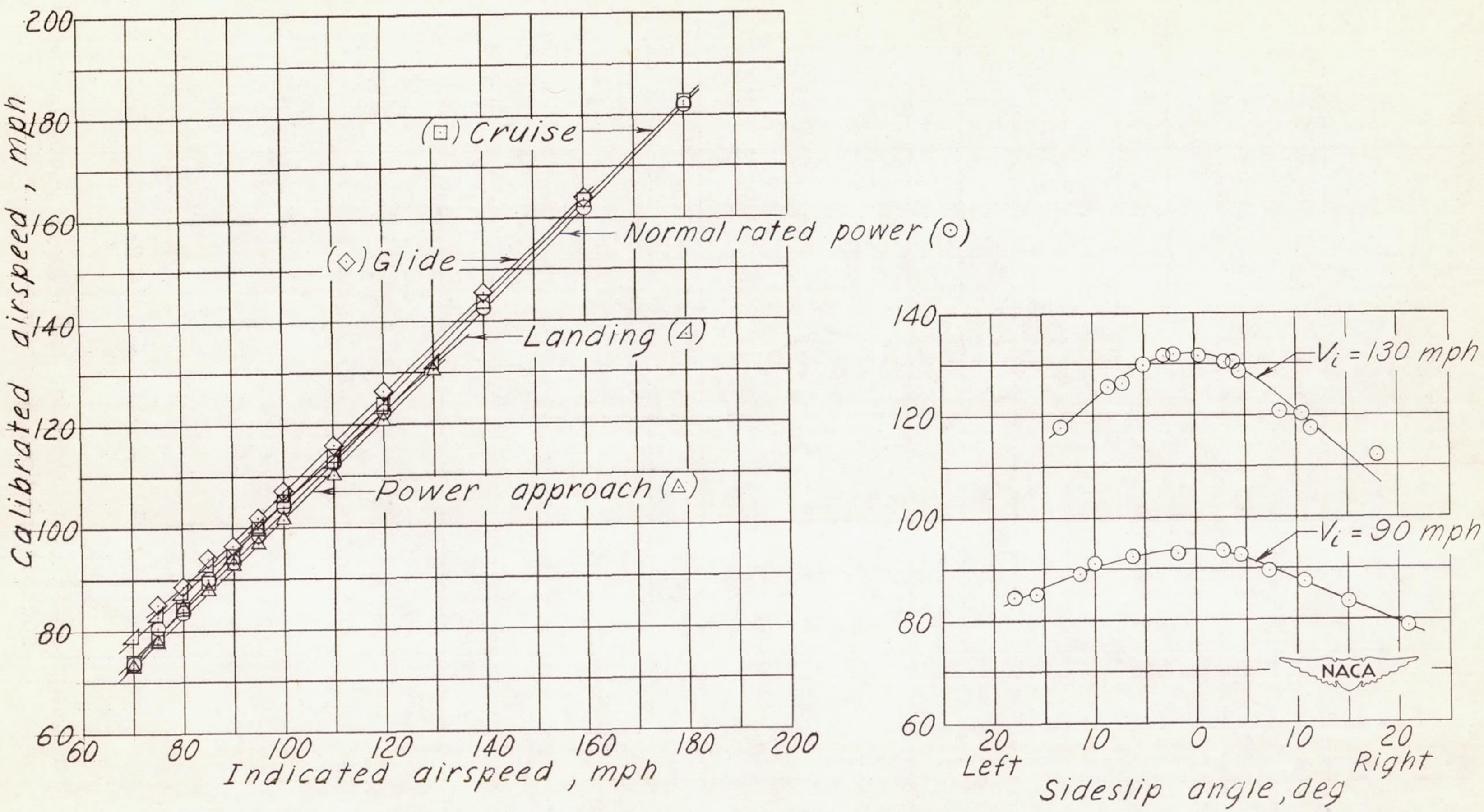
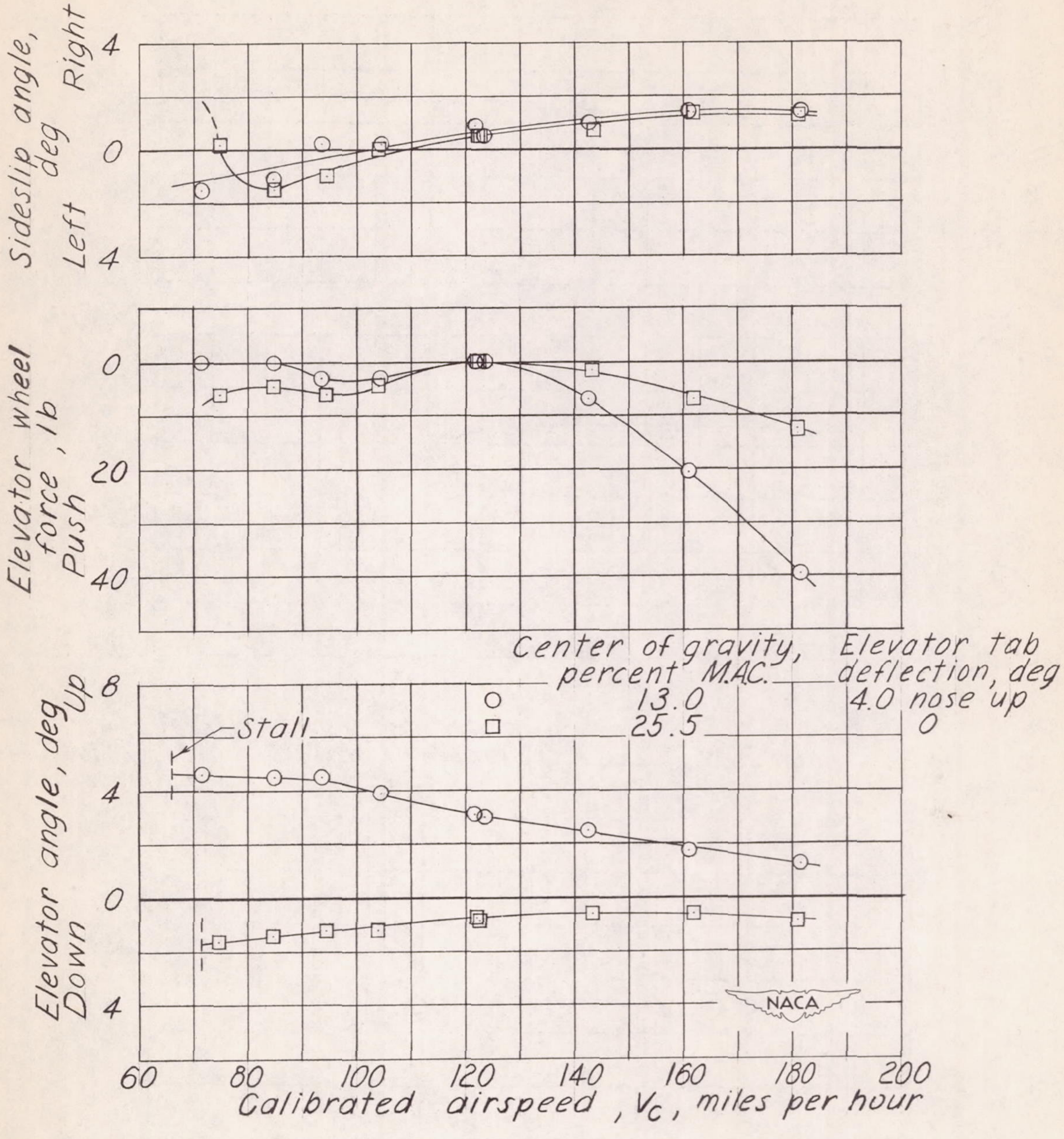
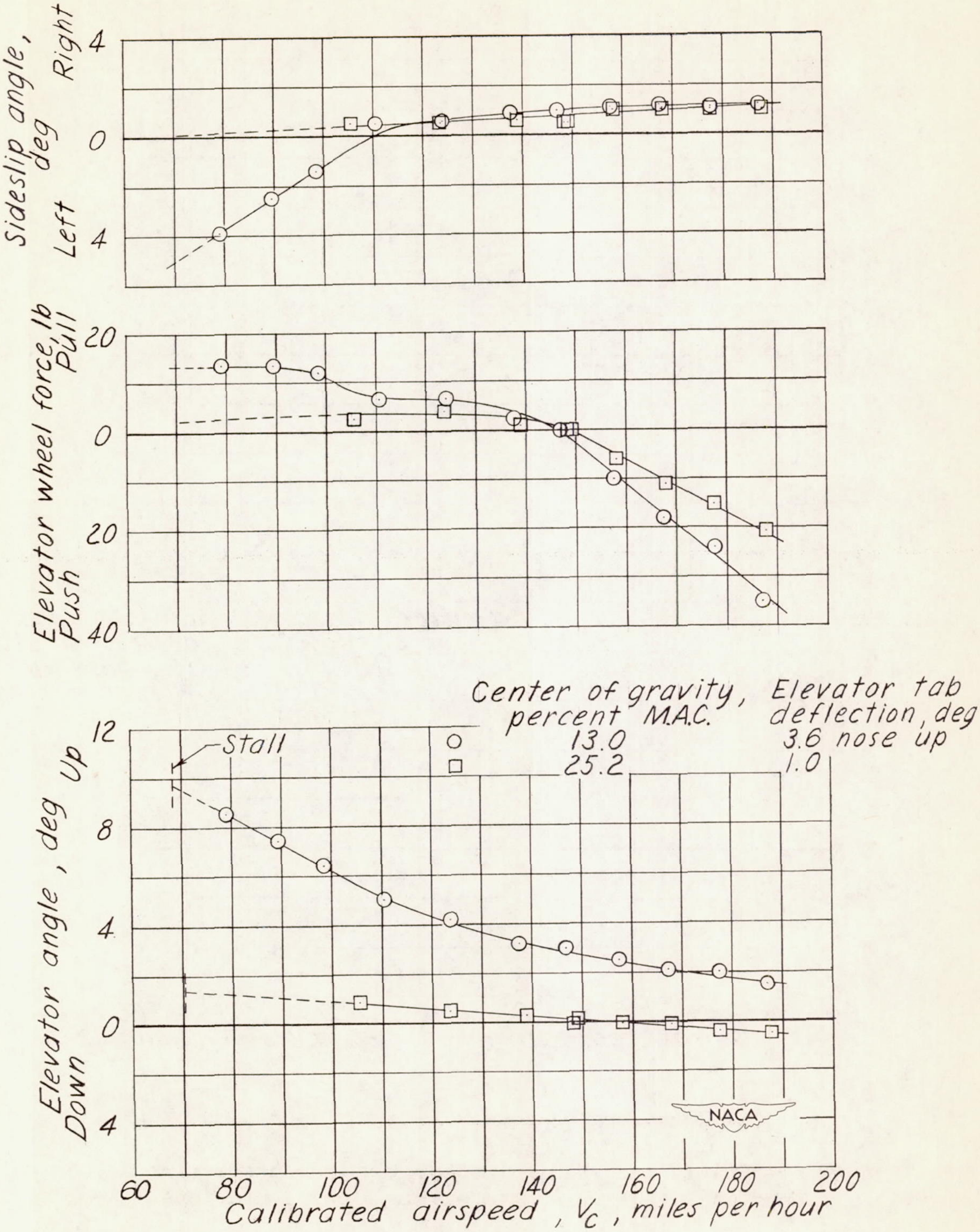


Figure 4.- Variation of calibrated airspeed with indicated airspeed for various airplane configurations and the variation of calibrated airspeed with sideslip angle for two indicated airspeeds in the normal-rated-power clean condition.



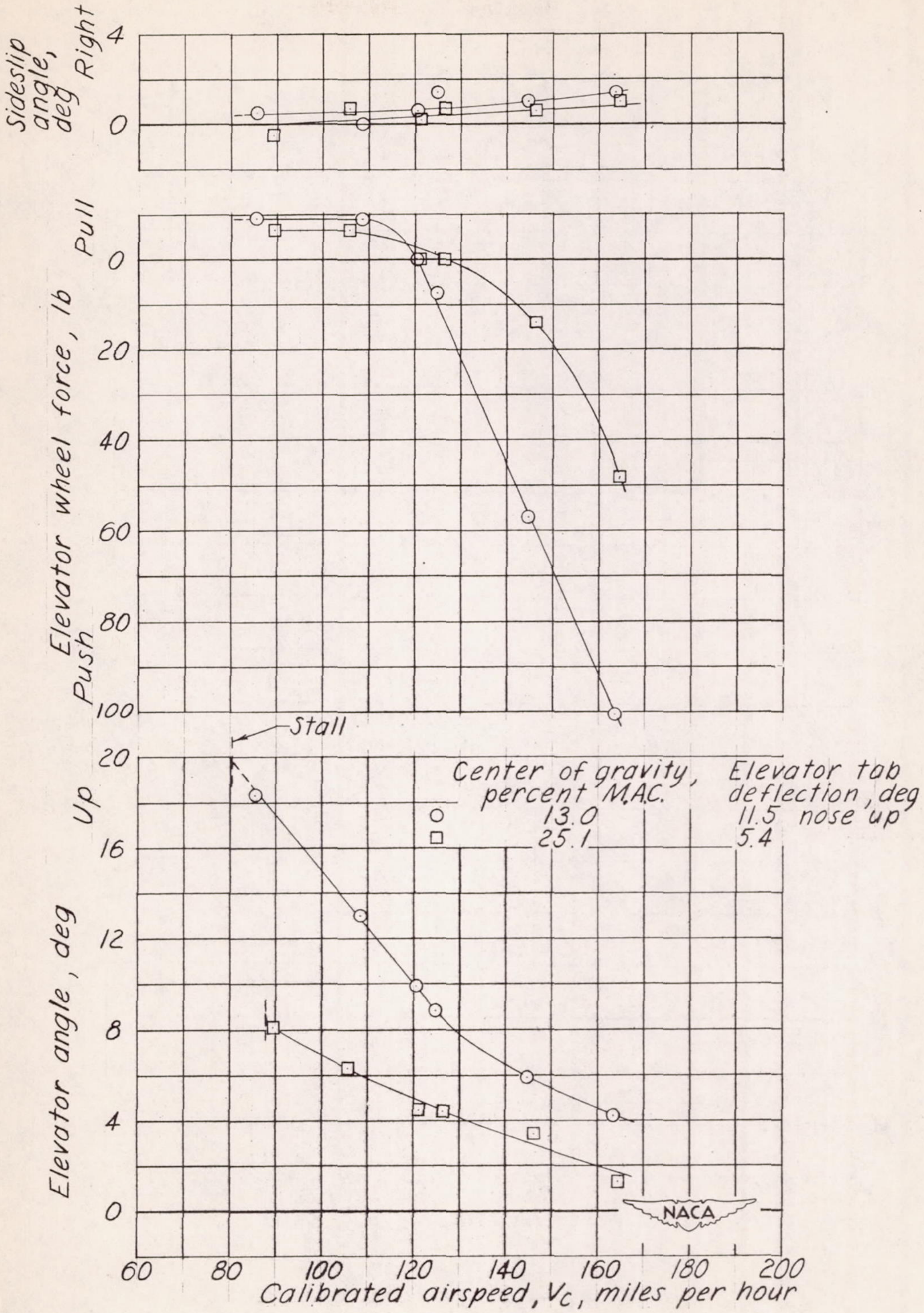
(a) Normal-rated-power clean configuration.

Figure 5.- Static longitudinal stability characteristics of the Douglas DC-3 airplane for various configurations.



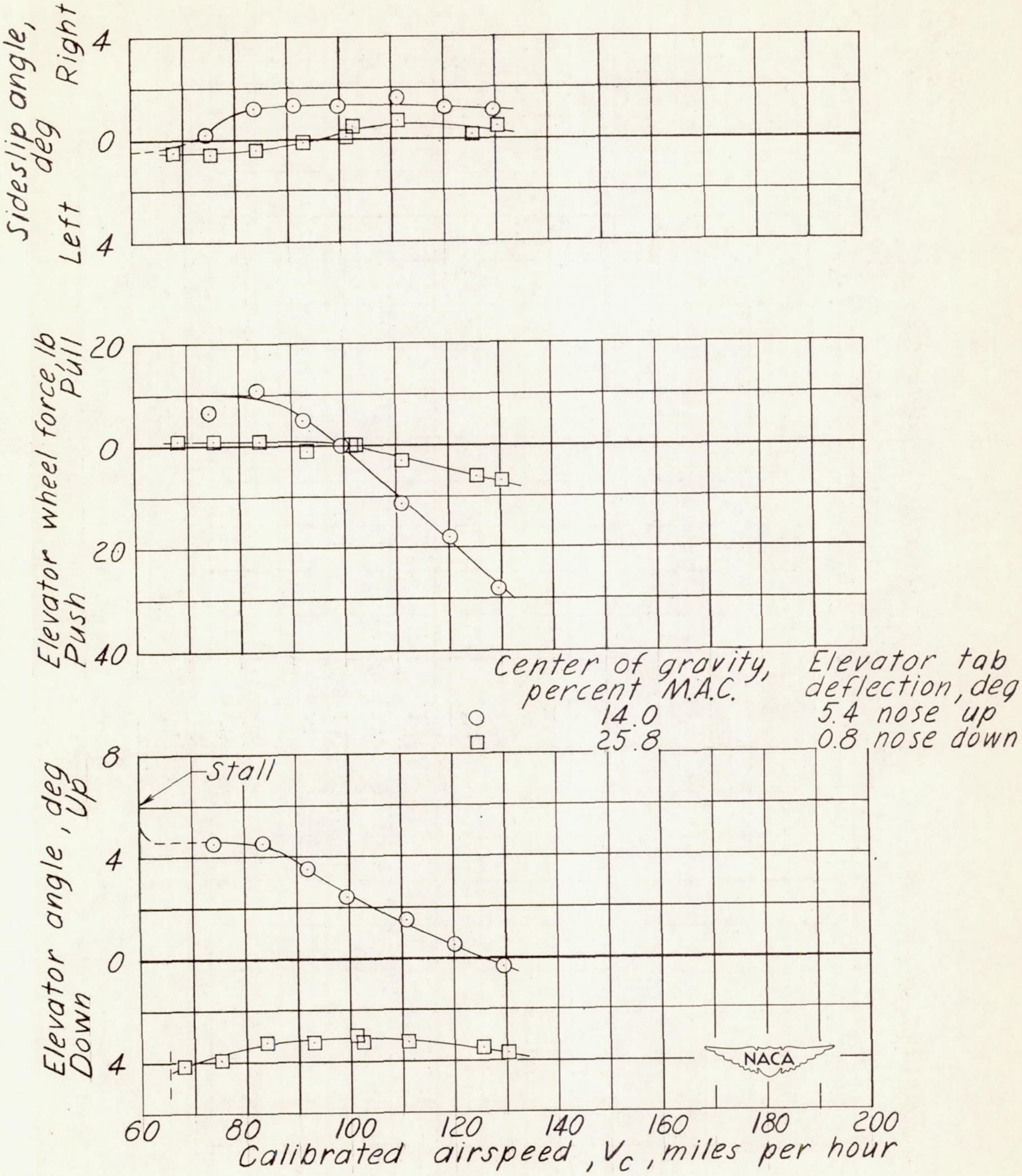
(b) Cruise configuration.

Figure 5.- Continued.



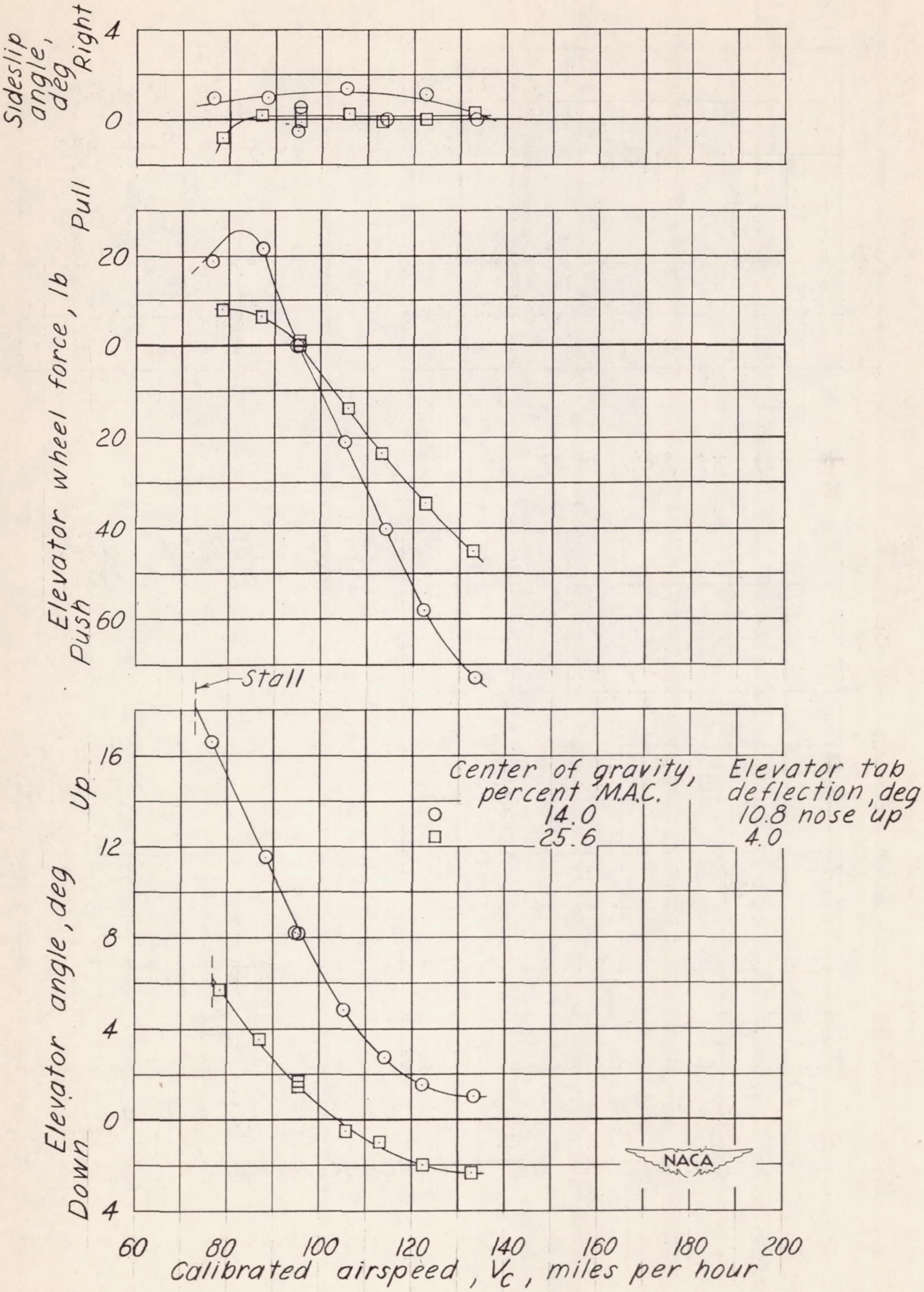
(c) Glide configuration.

Figure 5.- Continued.



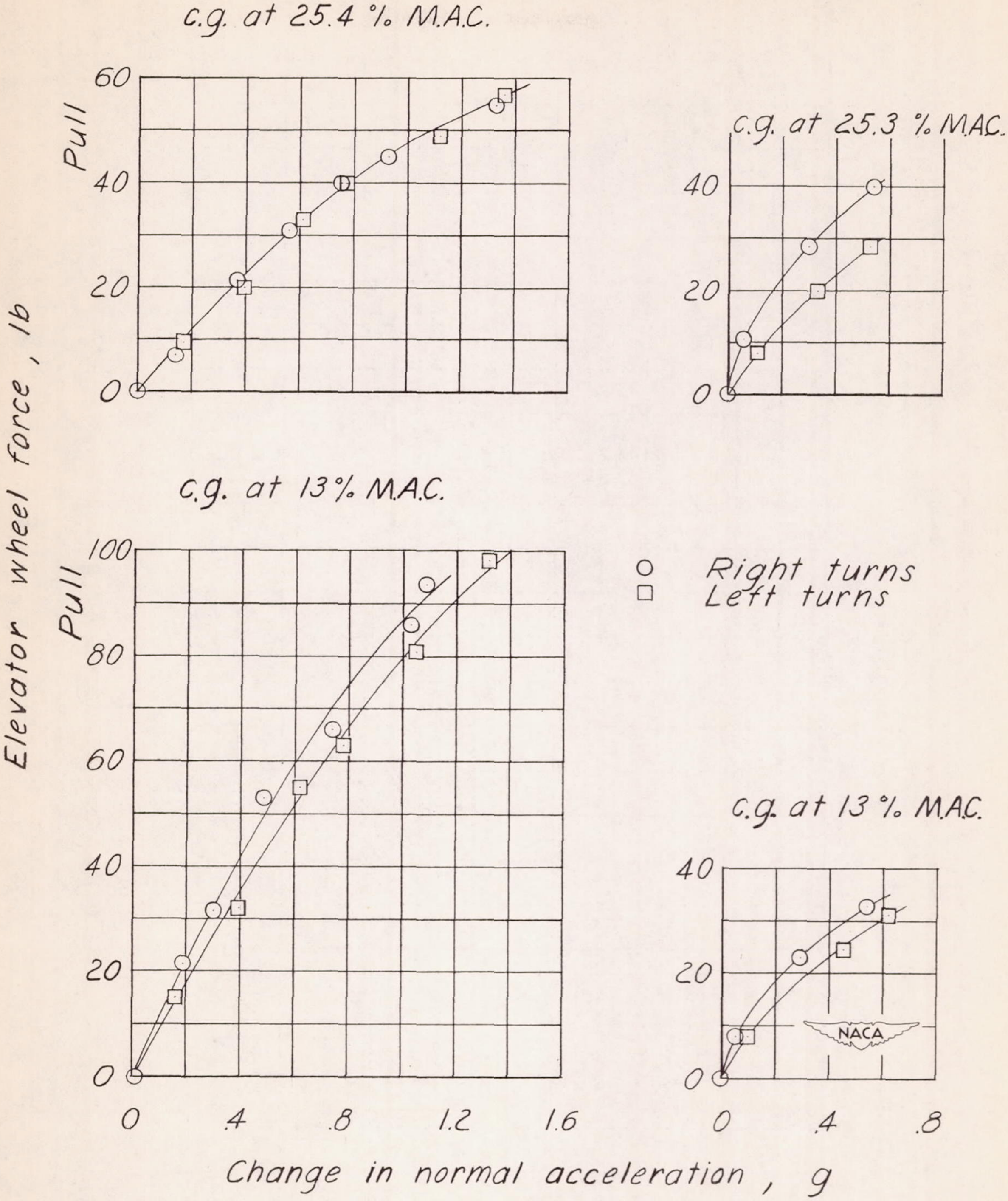
(d) Power-approach configuration.

Figure 5.- Continued.



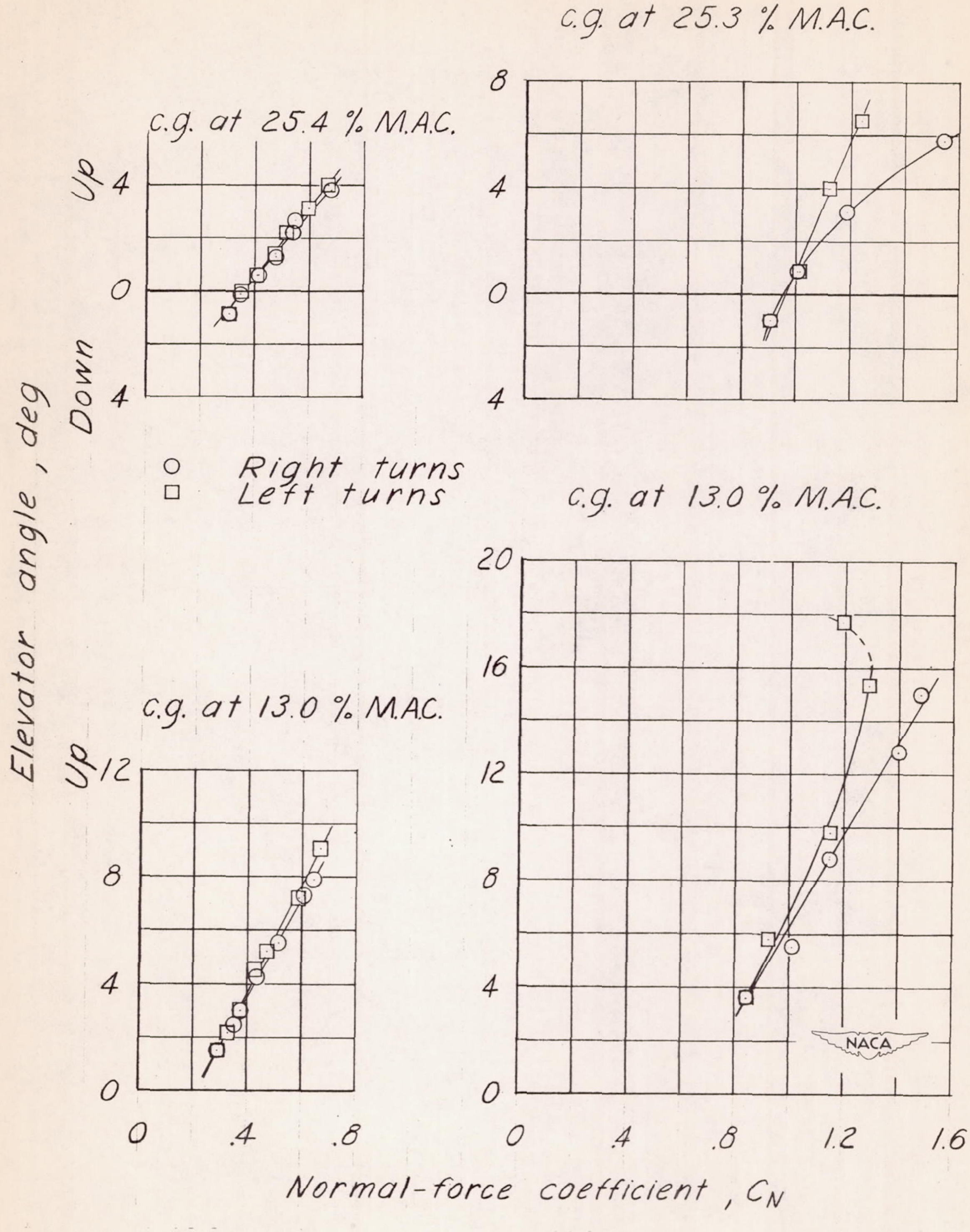
(e) Landing configuration.

Figure 5.- Concluded.



(a) V_i = 180 mph. (b) V_i = 100 mph.

Figure 6.- Variation of elevator wheel force with change in normal acceleration for constant-speed turns made with the Douglas DC-3 airplane in the normal-rated-power clean condition.



(a) V_i = 180 mph. (b) V_i = 100 mph.

Figure 7.- Variation of elevator angle with normal-force coefficient for constant-speed turns made with the Douglas DC-3 airplane in the normal-rated-power clean condition.

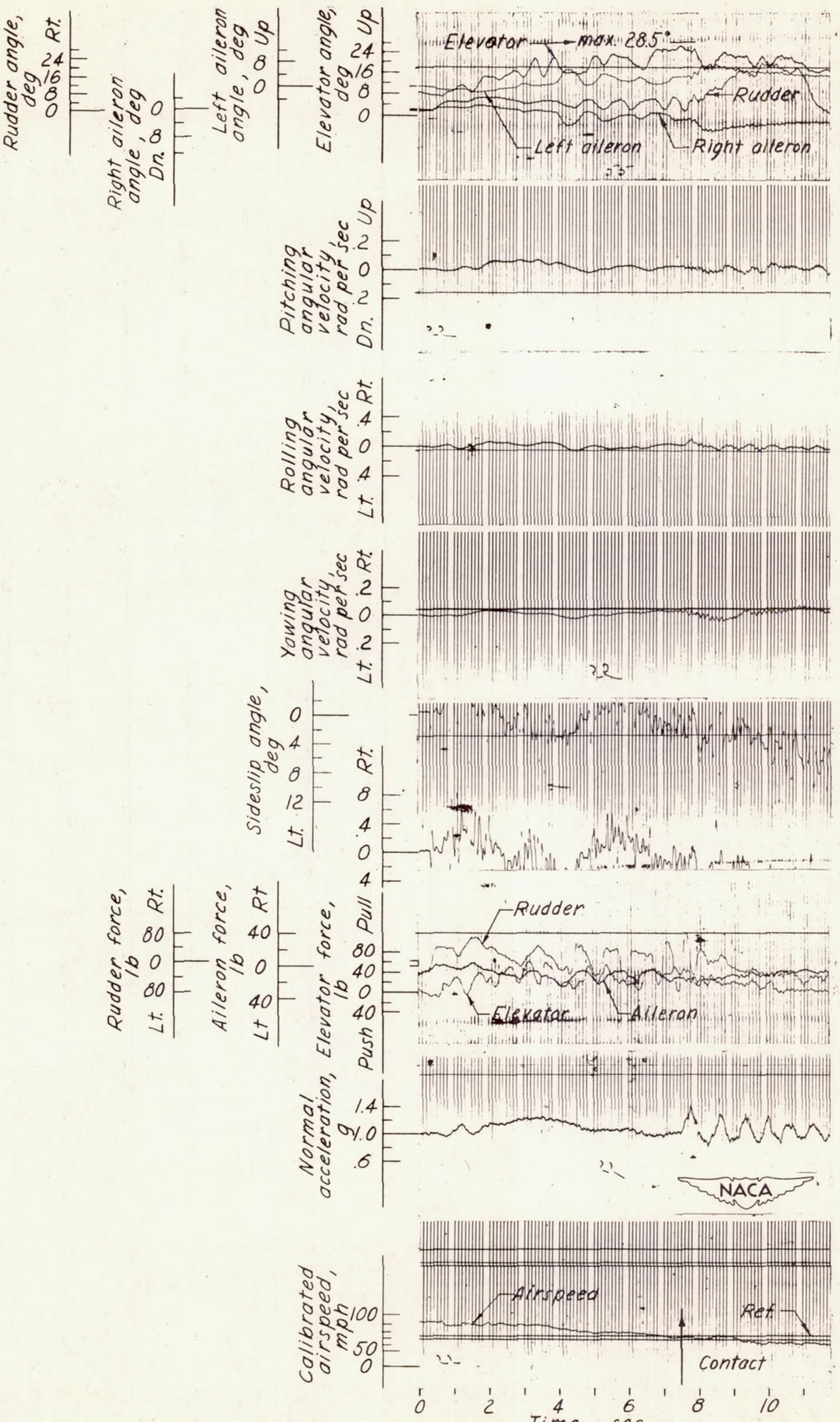


Figure 8.- Time history of a typical landing of a Douglas DC-3 airplane.

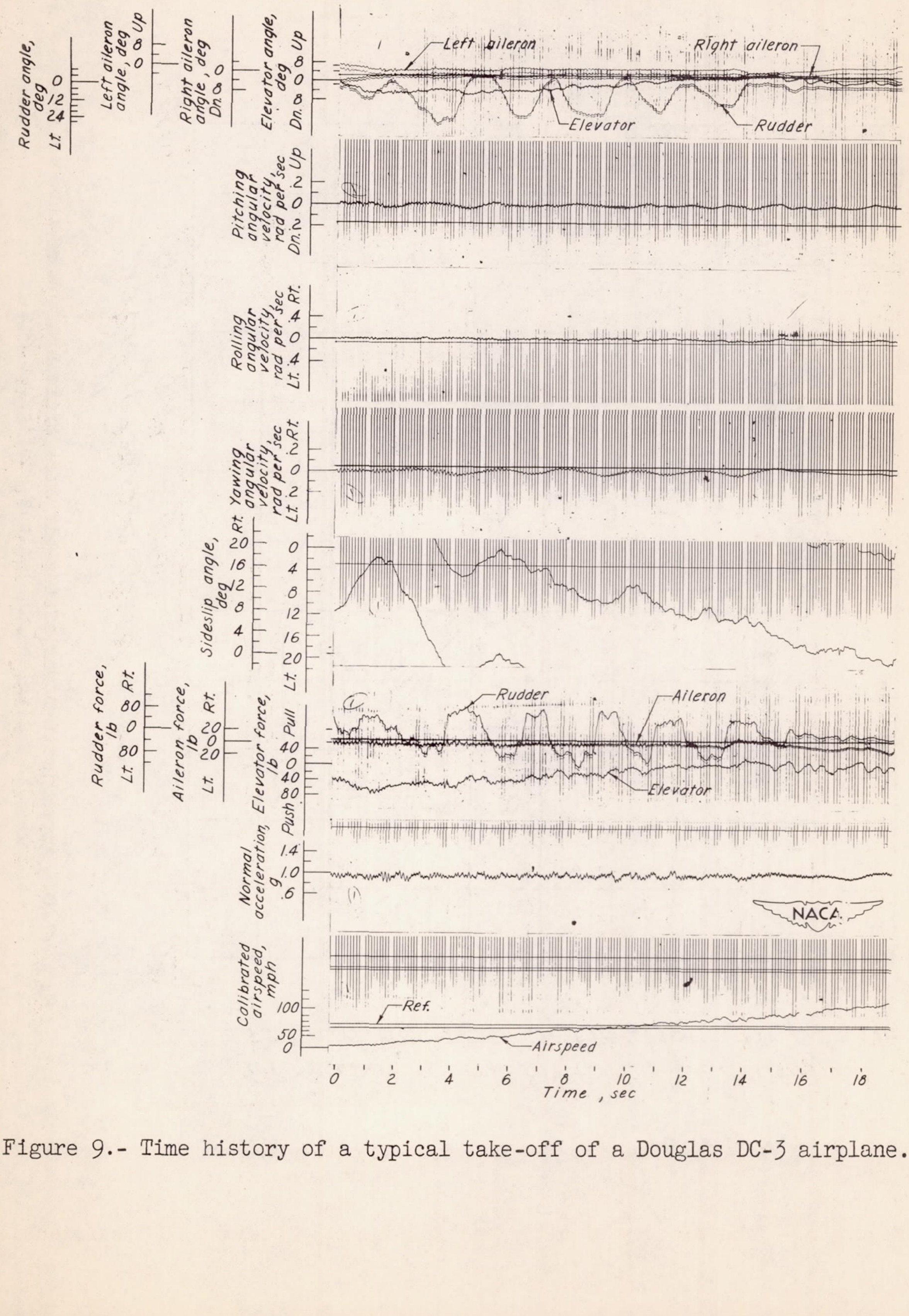


Figure 9.- Time history of a typical take-off of a Douglas DC-3 airplane.

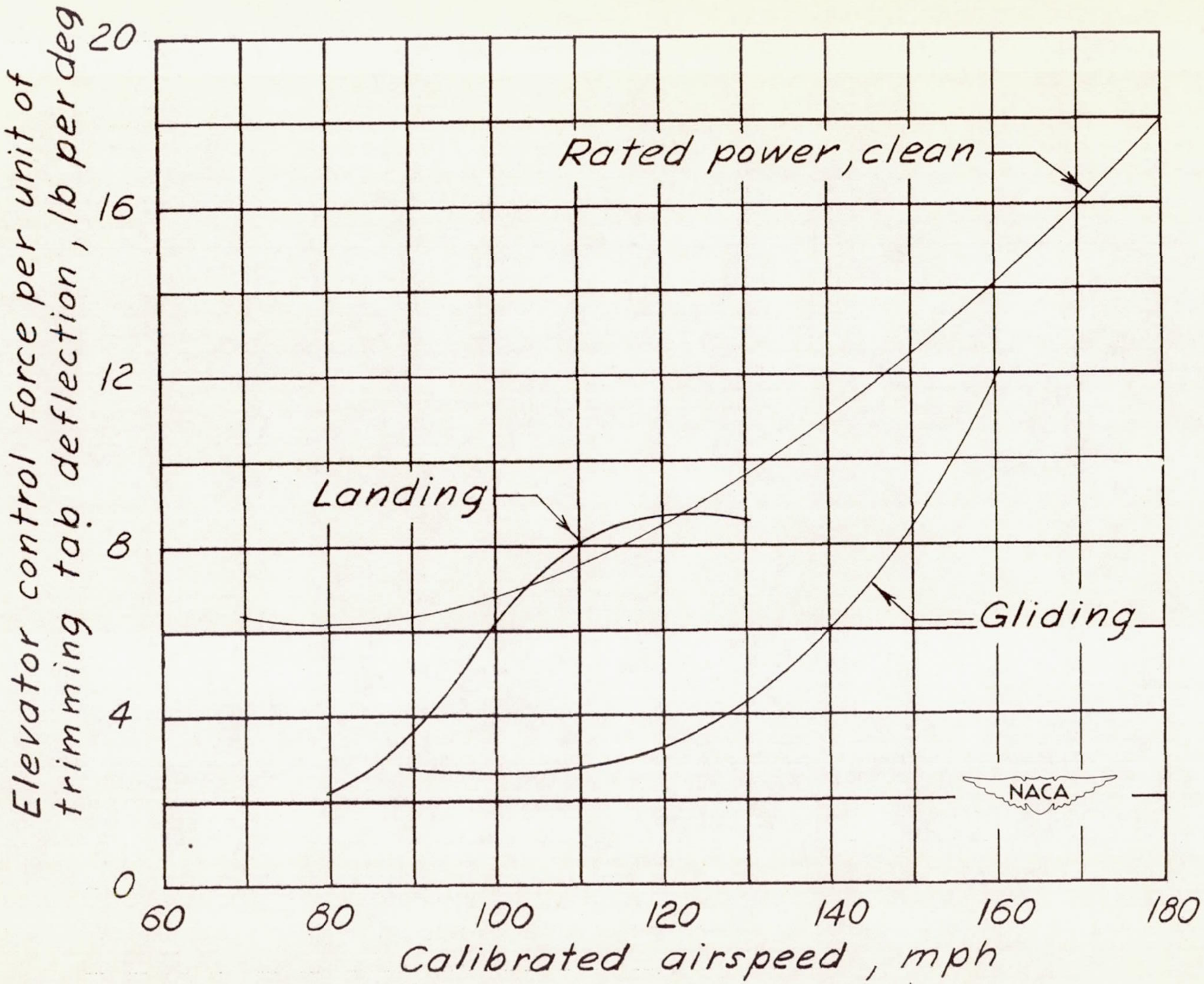
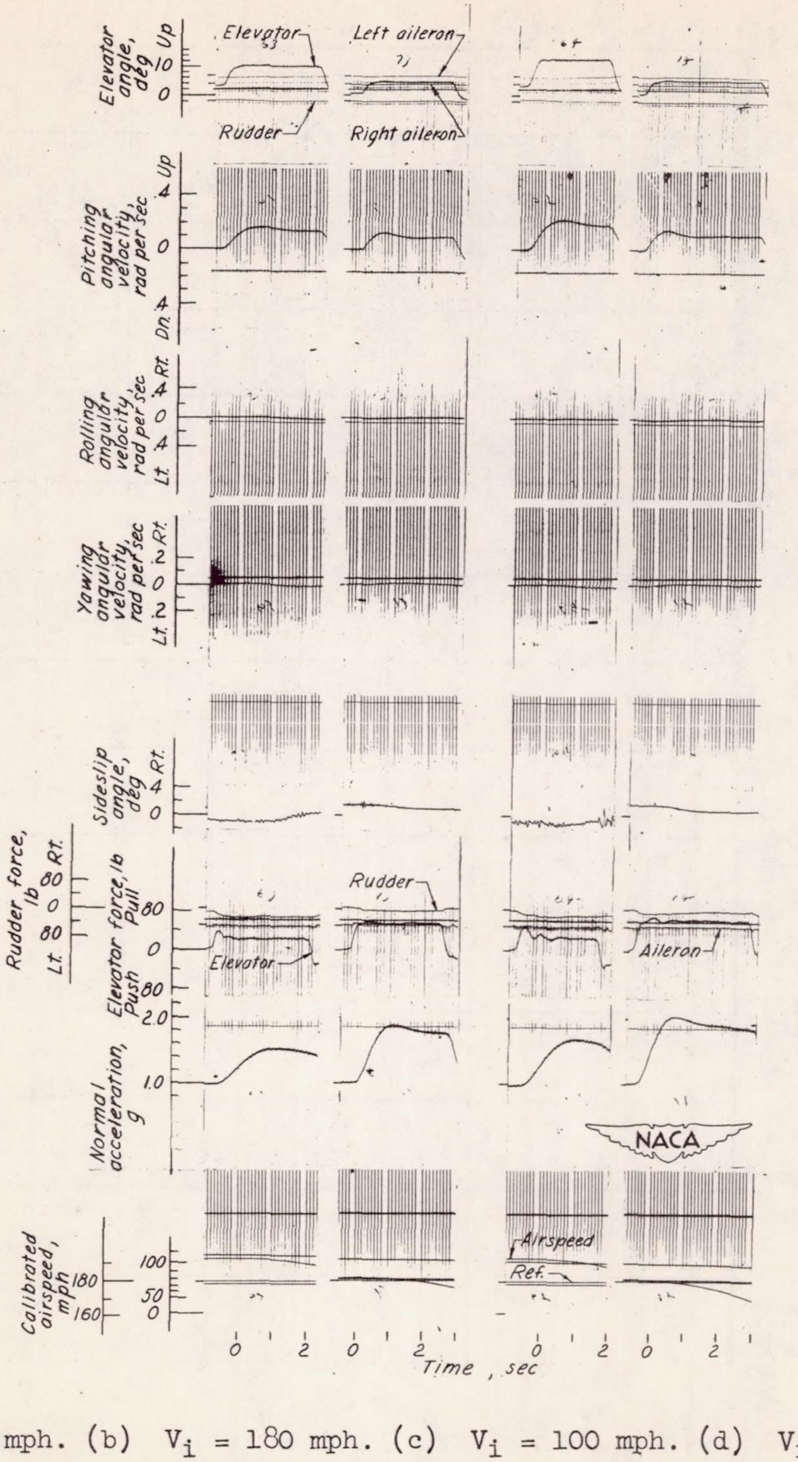


Figure 10.- Approximate power of the elevator trimming tabs of the Douglas DC-3 airplane in various configurations.



(a) V_i = 100 mph. (b) V_i = 180 mph. (c) V_i = 100 mph. (d) V_i = 180 mph.

Figure 11.- Typical time histories of responses to step elevator deflections made with the Douglas DC-3 airplane in the clean configuration. Center-of-gravity position, 12.5 percent M.A.C.; gross weight, 23,000 pounds; altitude, 5,000 feet.

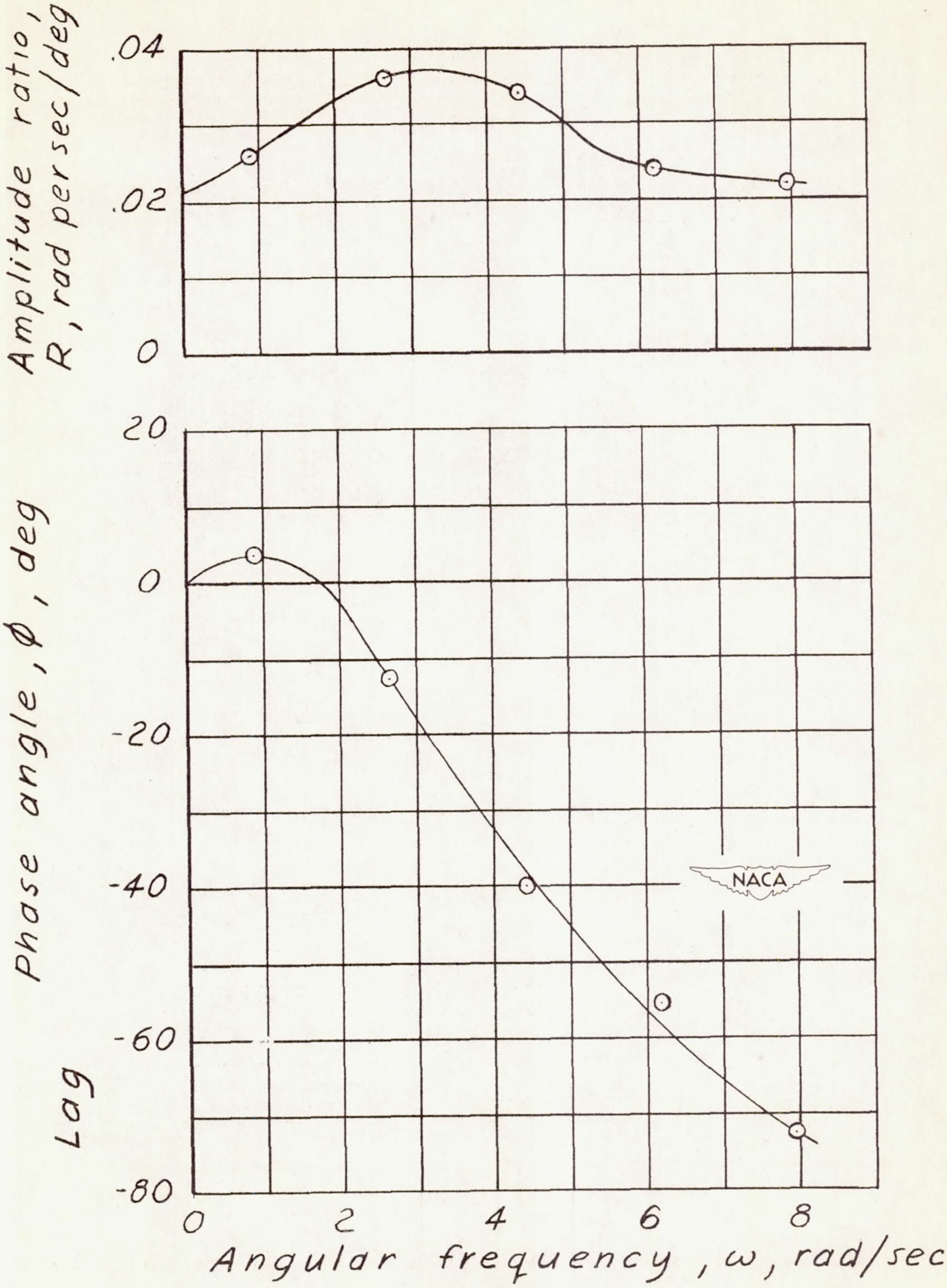
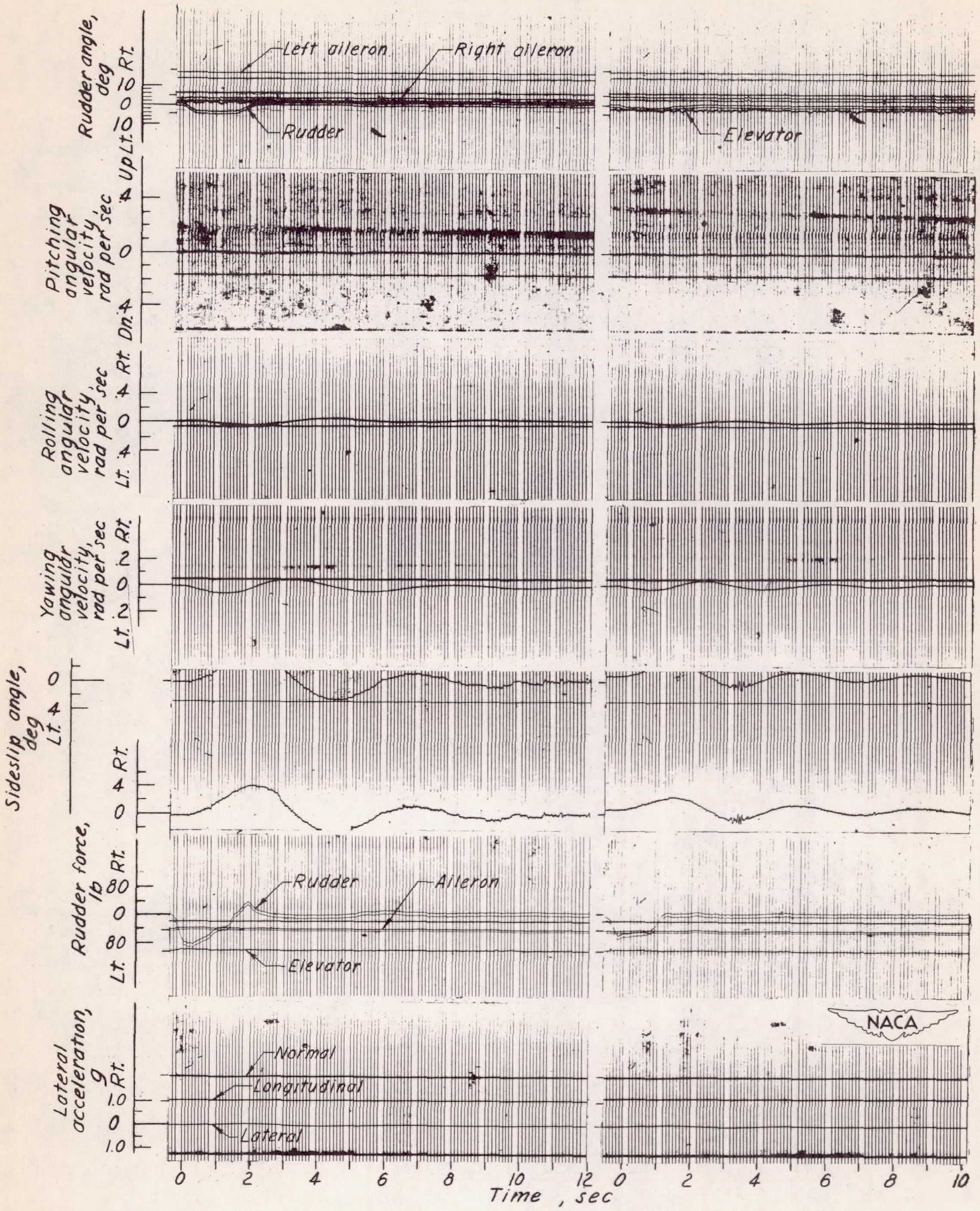
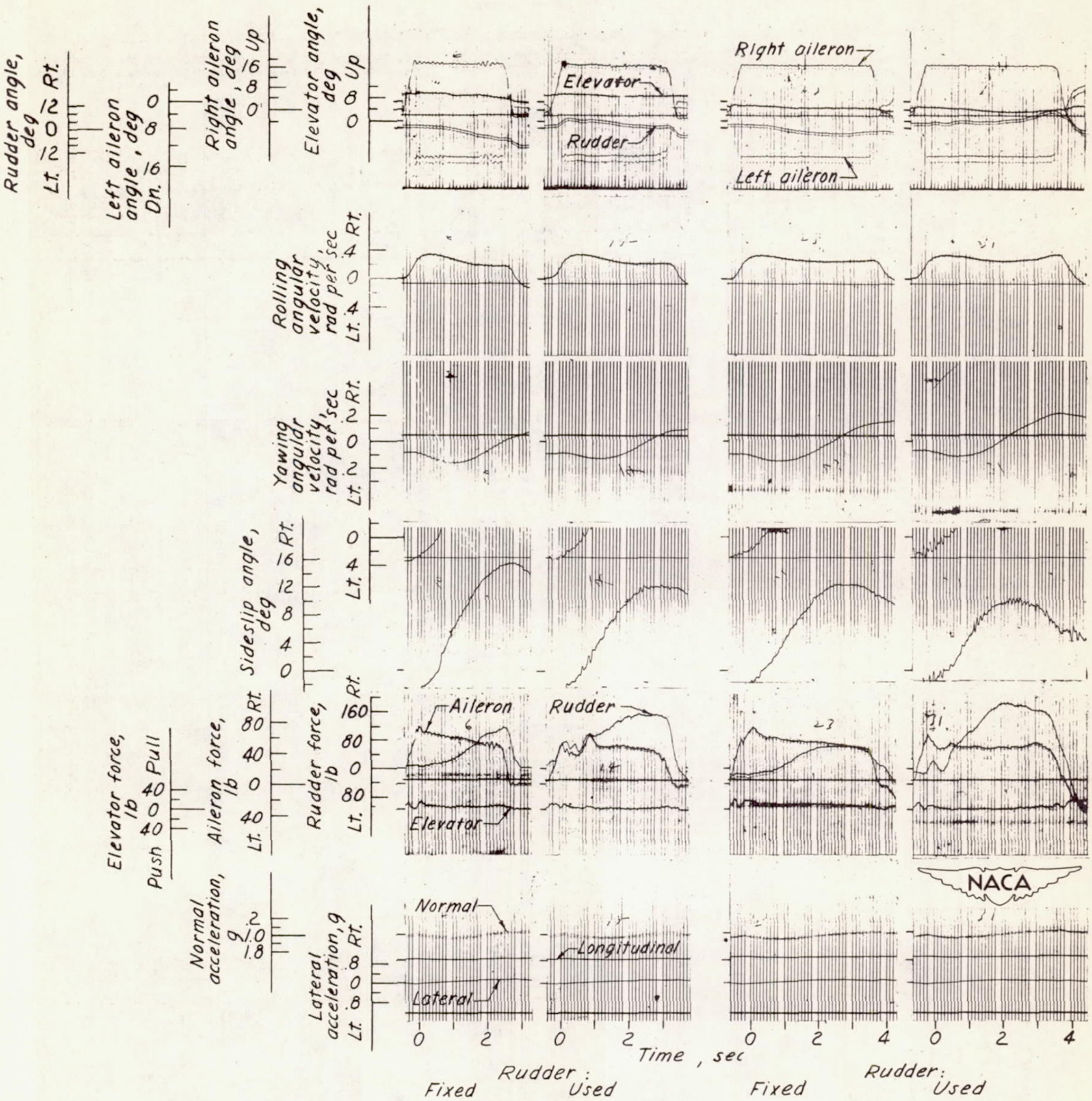


Figure 12.- Frequency response of pitching velocity to elevator deflection of a Douglas DC-3 airplane in the clean condition at an indicated airspeed of 180 mph. Center-of-gravity position, 12.5 percent M.A.C.



(a) V_i = 120 mph. (b) V_i = 170 mph.

Figure 13.- Typical time histories of rudder kicks made with the Douglas DC-3 airplane in the cruise configuration. Center-of-gravity position, 13.0 percent M.A.C.; gross weight, 24,000 pounds; altitude, 6,000 feet.



(a) Clean condition. (b) Power-approach condition.

Figure 14.- Typical time histories of right rolls out of 30° banked turns at an indicated airspeed of 100 mph for the Douglas DC-3 in two configurations.

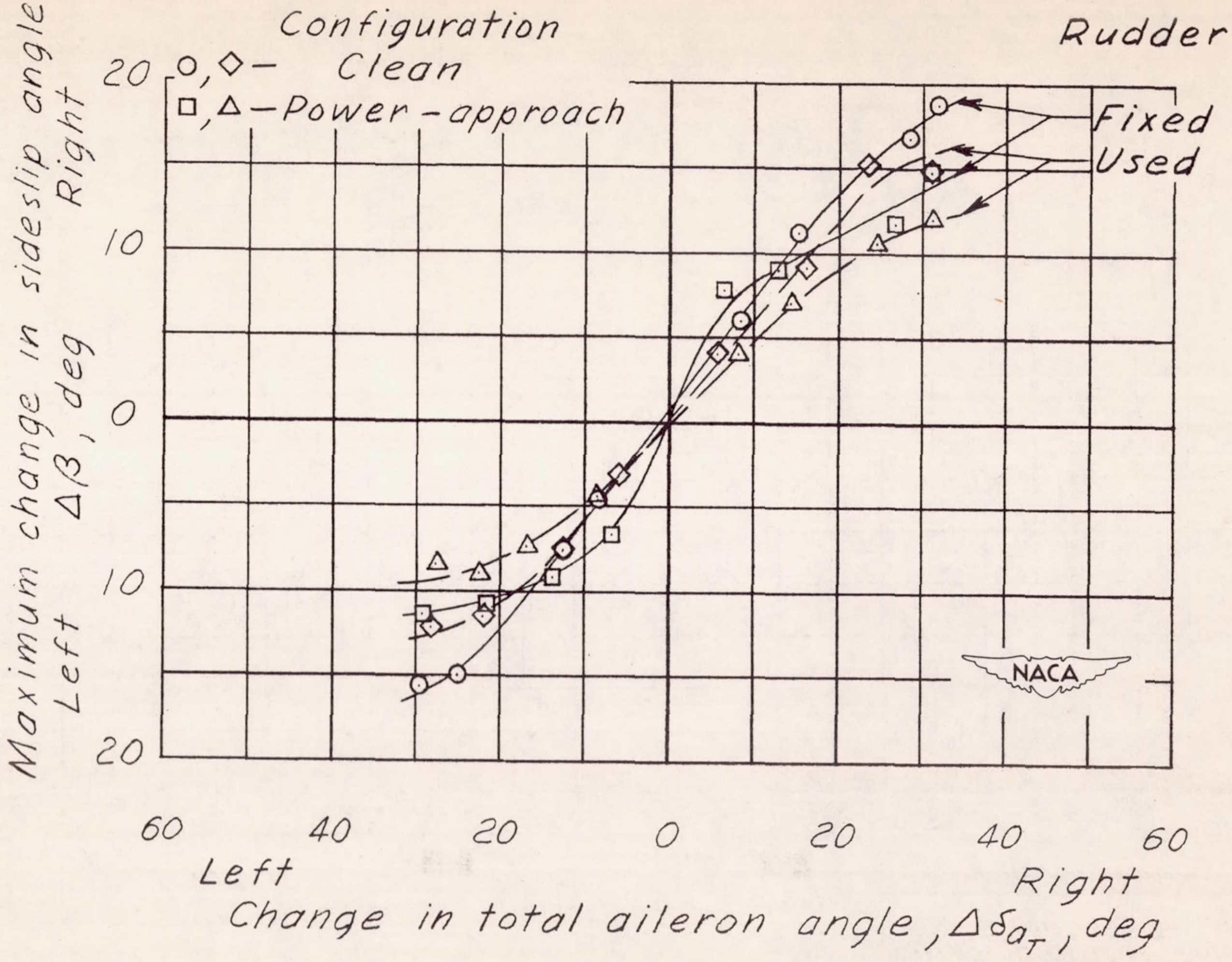
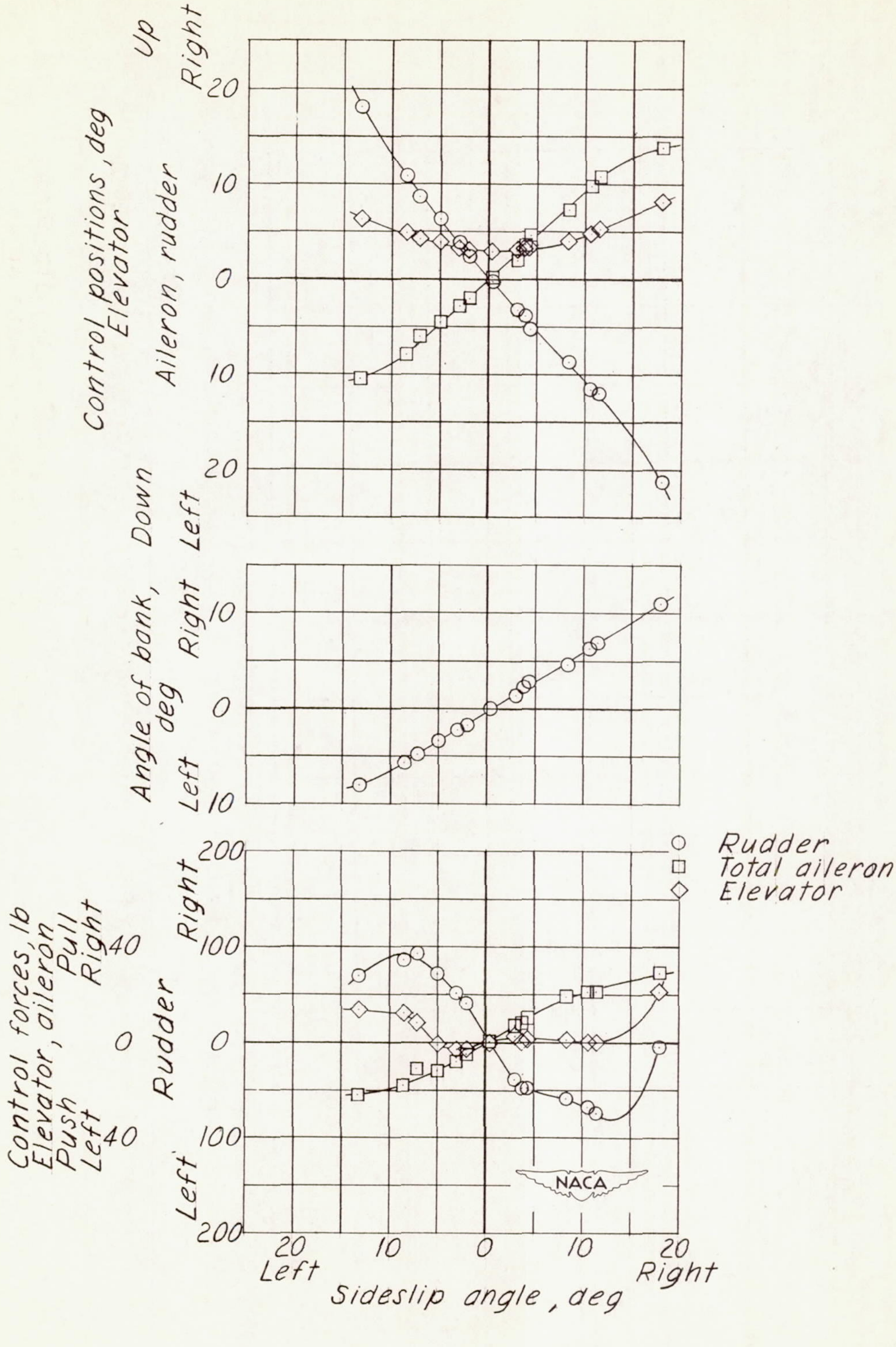
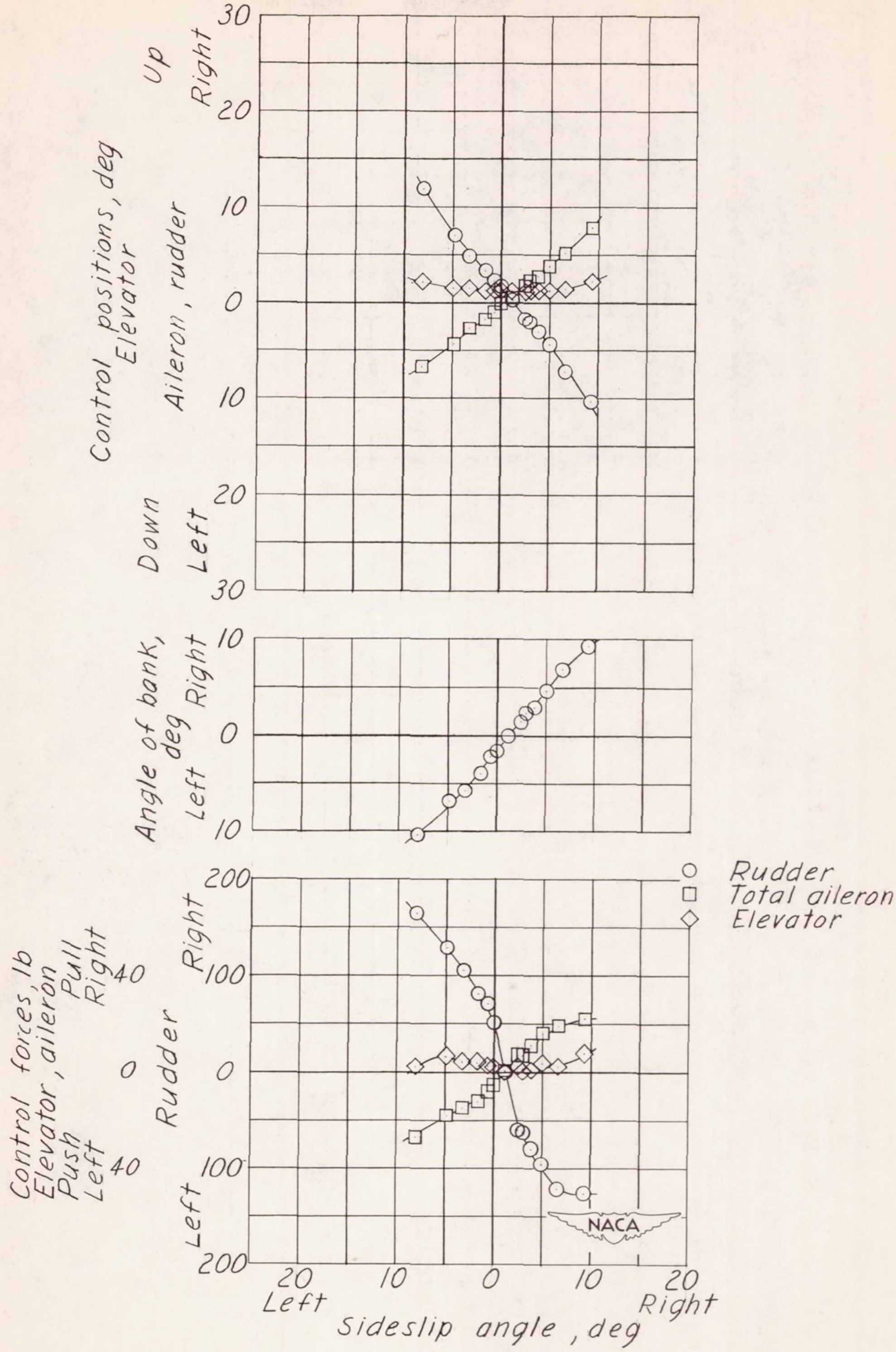


Figure 15.- Variation of the maximum change in sideslip angle with change in total aileron angle for several rolls out of steady turns at an indicated airspeed of 100 mph for two configurations of the Douglas DC-3 airplane.



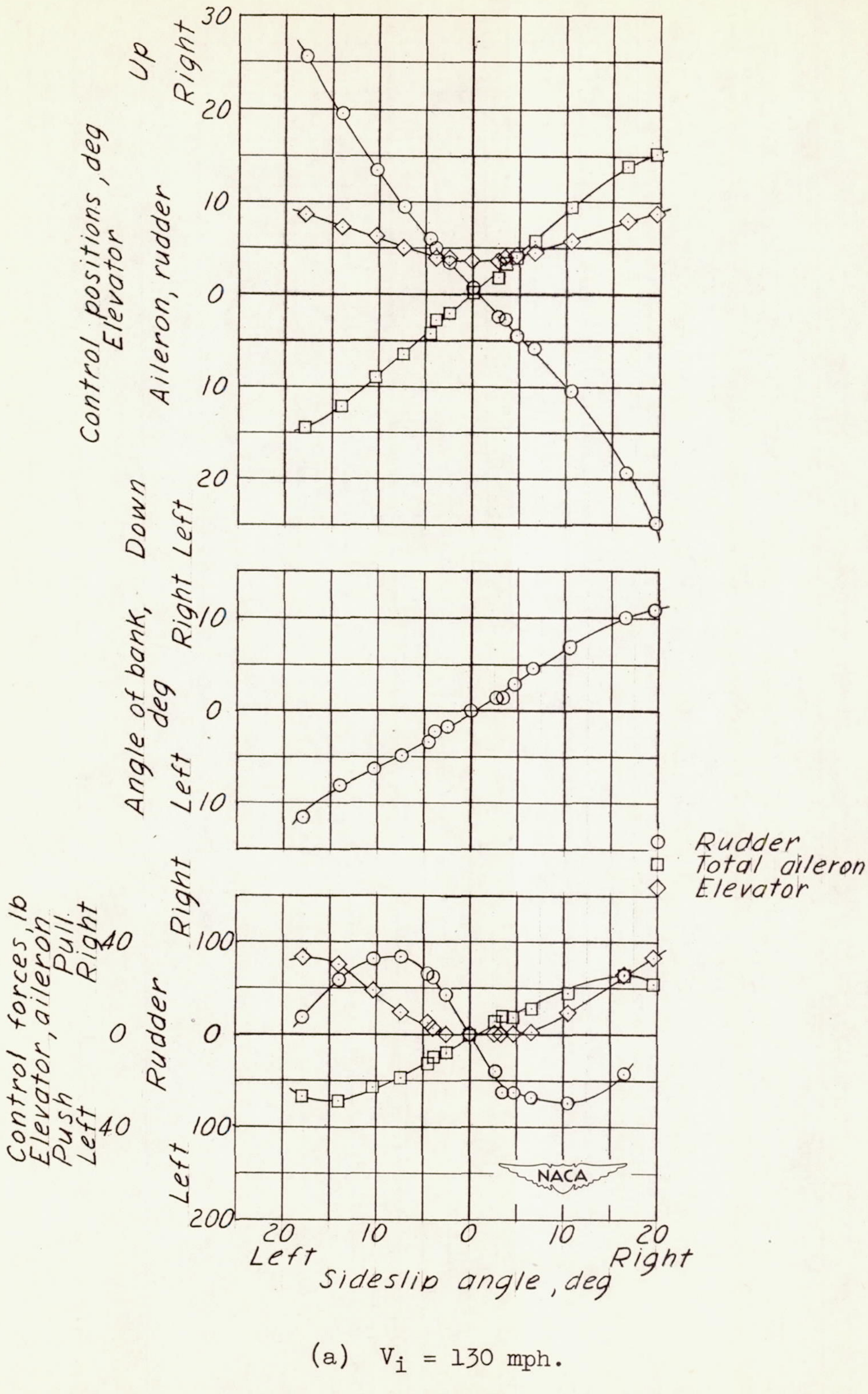
(a) V_i = 130 mph.

Figure 16.- Sideslip characteristics of the Douglas DC-3 airplane in the normal-rated-power clean condition.



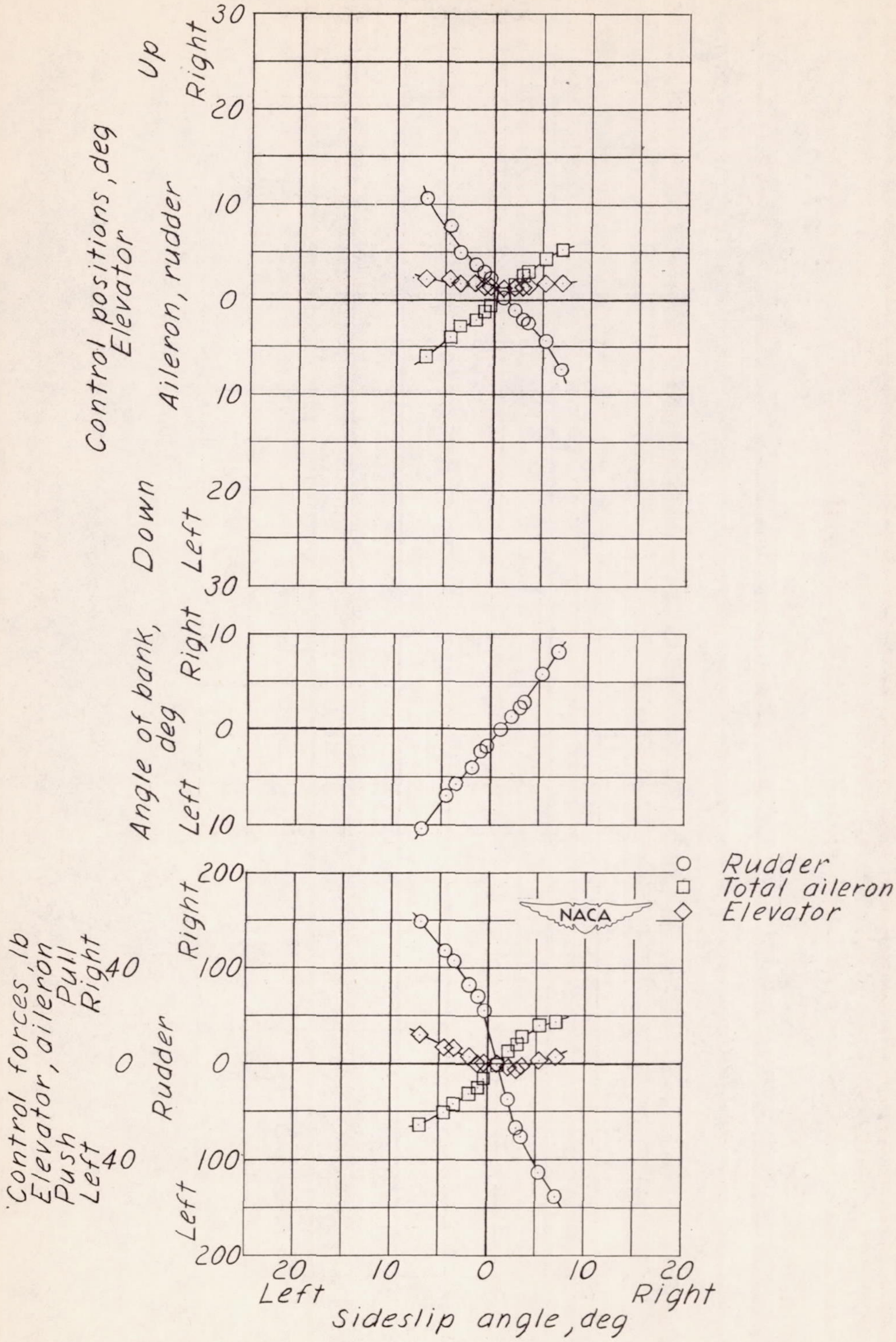
(b) V_i = 180 mph.

Figure 16.- Concluded.



(a) V_i = 130 mph.

Figure 17.- Sideslip characteristics of the Douglas DC-3 airplane in the cruising condition.



(b) V_i = 180 mph.

Figure 17.- Concluded.

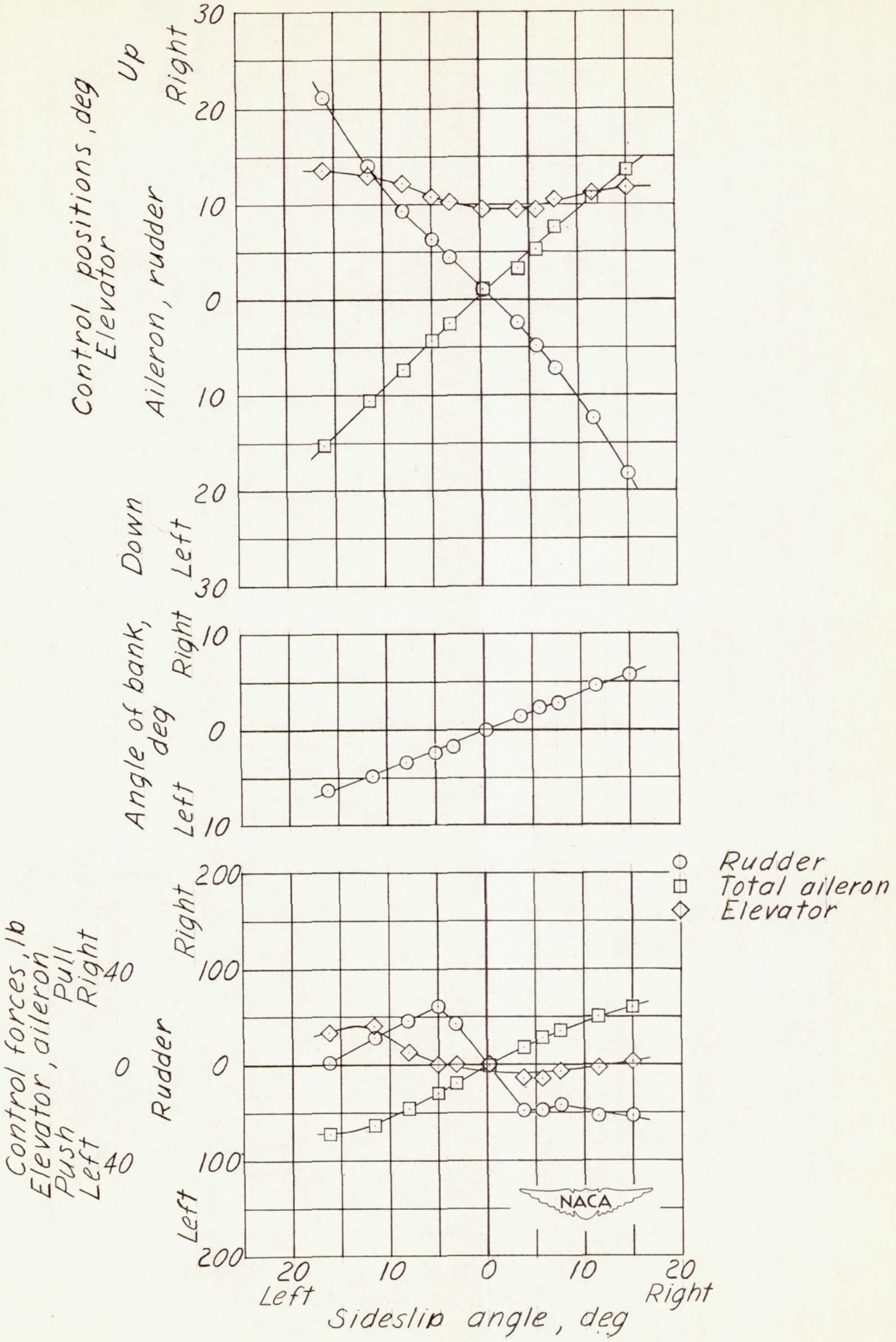
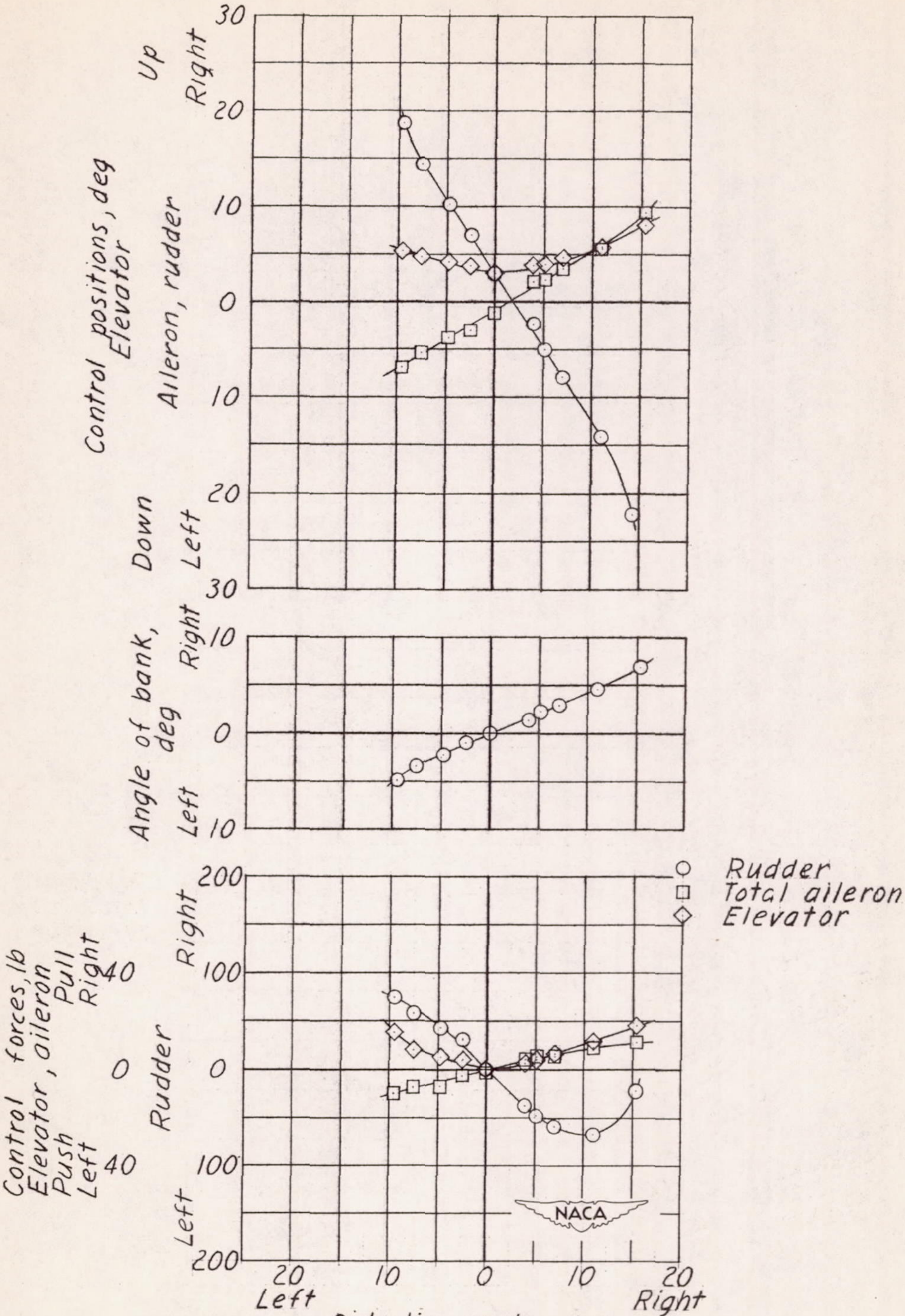
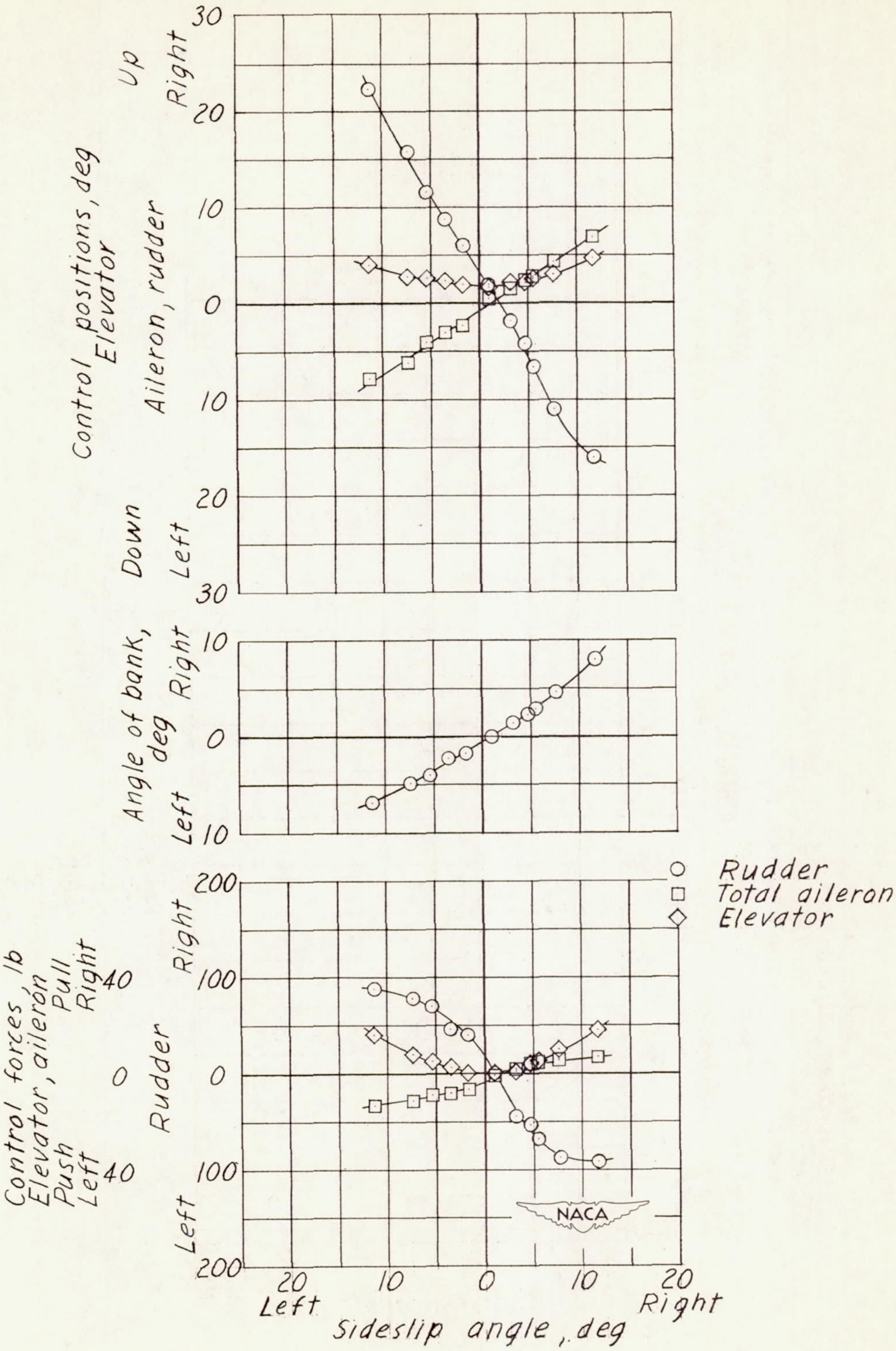


Figure 18.- Sideslip characteristics of the Douglas DC-3 airplane in the gliding configuration at an airspeed of V_i = 115 mph.



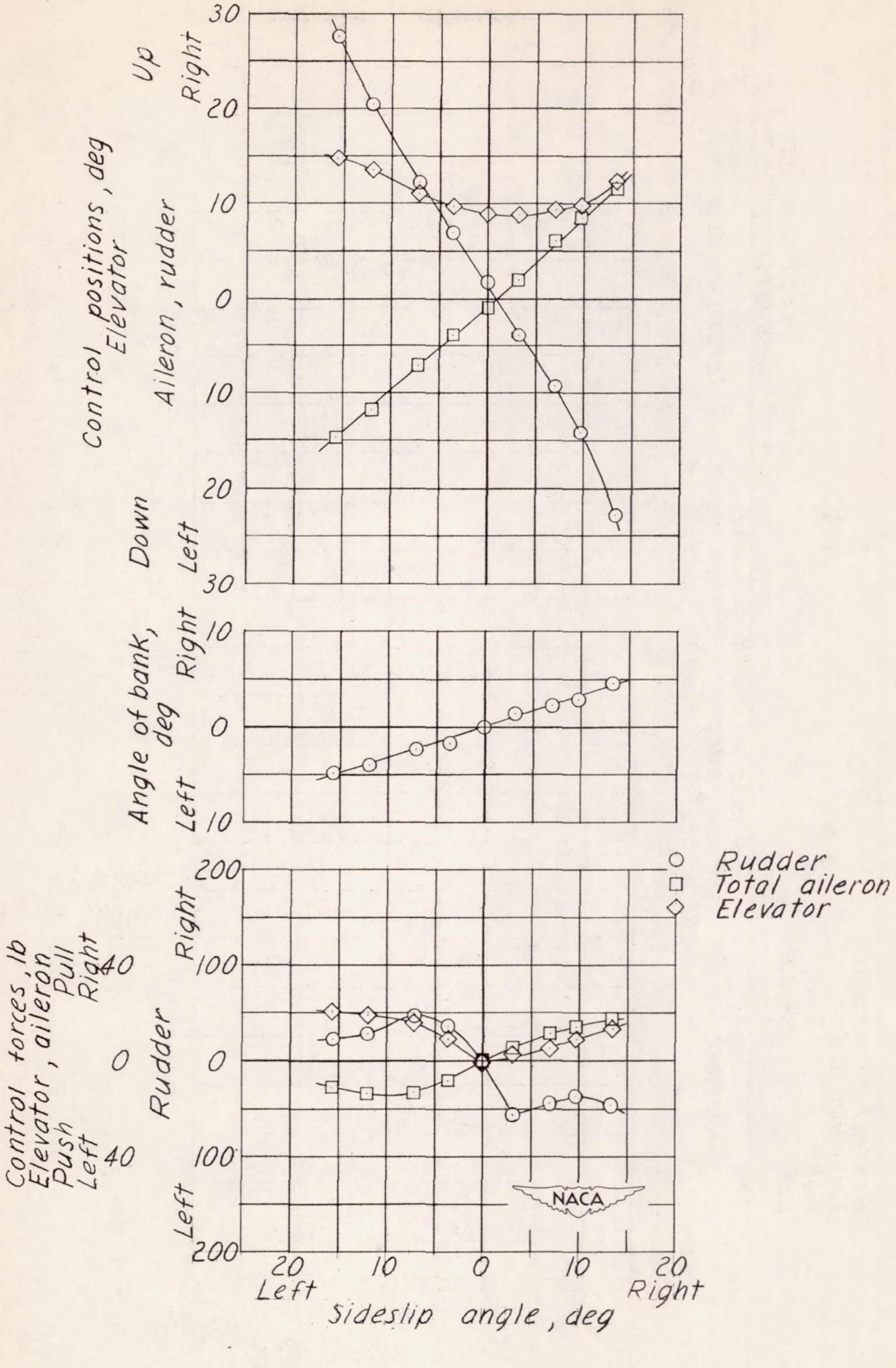
(a) $V_i = 95$ mph.

Figure 19.- Sideslip characteristics of the Douglas DC-3 airplane in the power-approach condition.



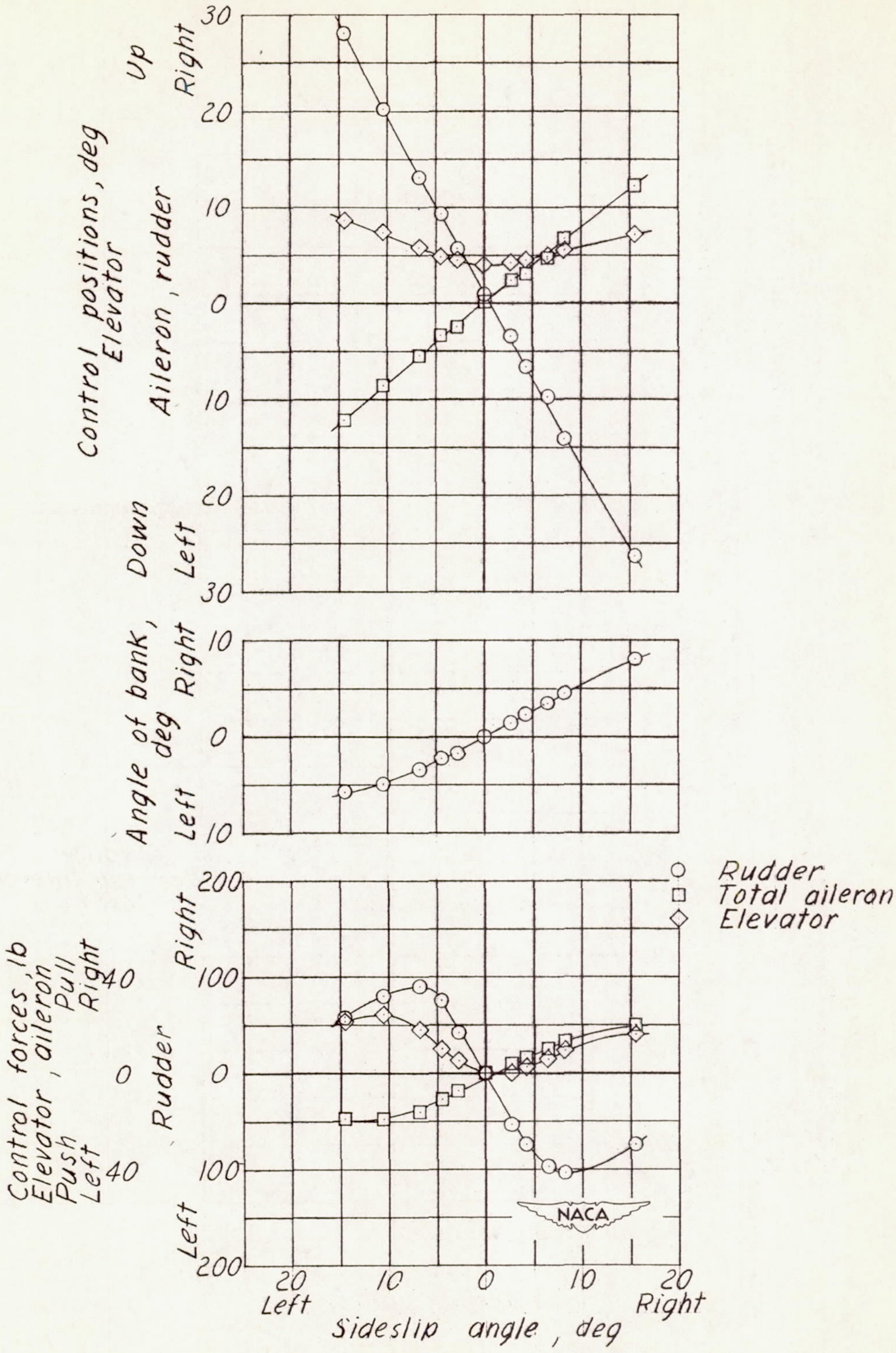
(b) V_i = 110 mph.

Figure 19.- Concluded.



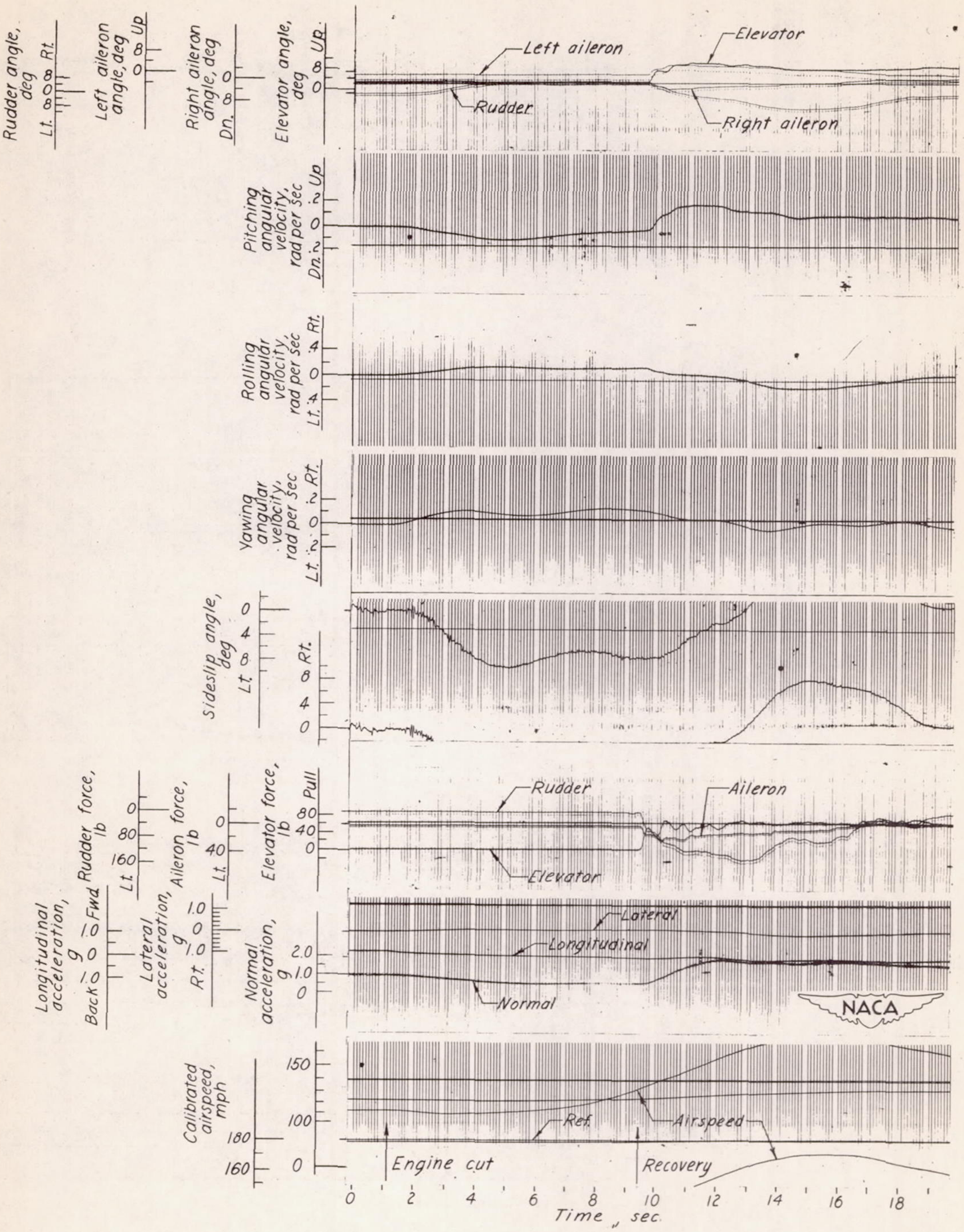
(a) V_i = 90 mph.

Figure 20.- Sideslip characteristics of the Douglas DC-3 in the landing condition.



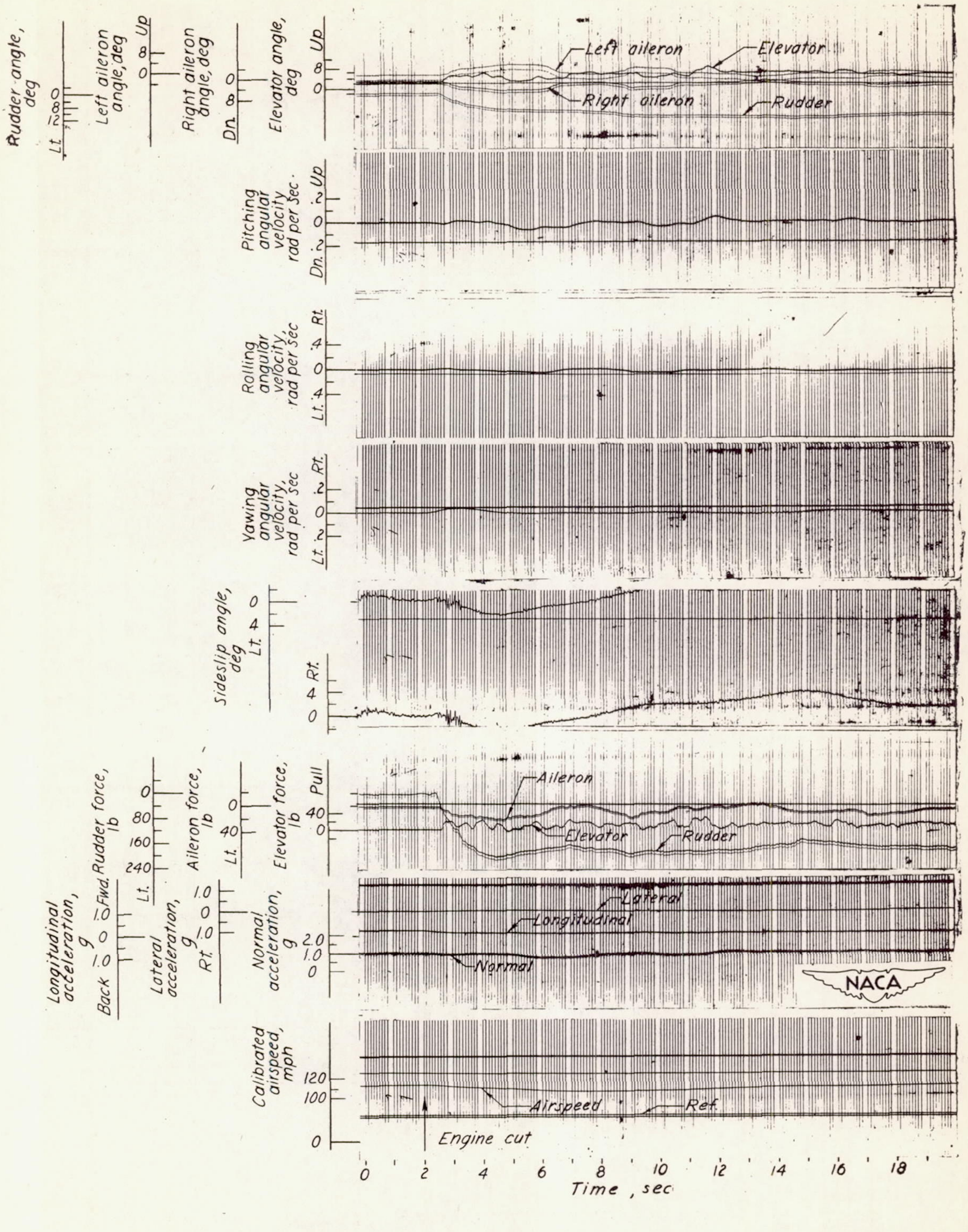
(b) V_i = 110 mph.

Figure 20.- Concluded.



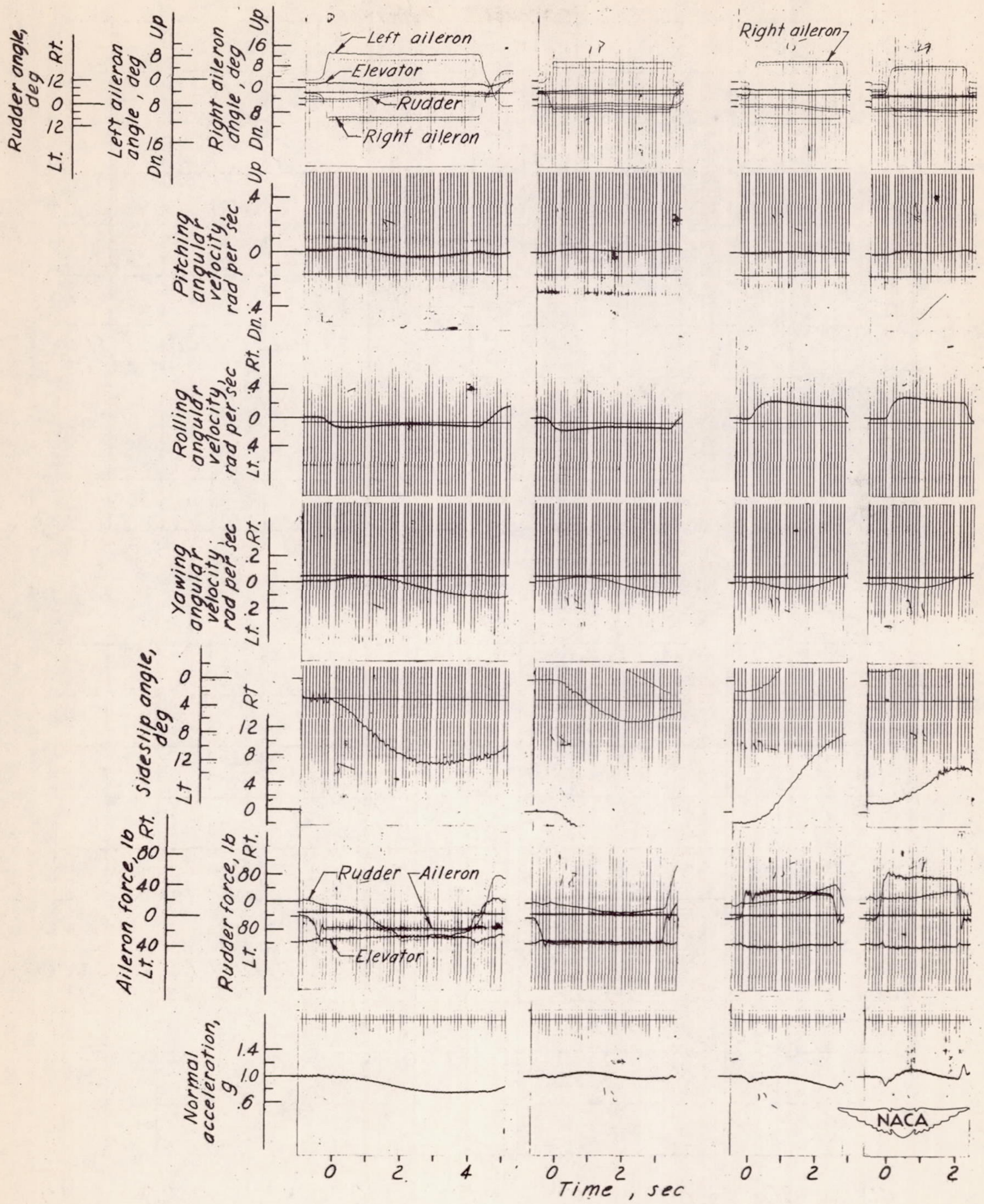
(a) No corrective control applied.

Figure 21.- Time histories of the motions resulting from the loss in power of the right engine (propeller windmilling and in low pitch) of the Douglas DC-3 airplane while in the take-off configuration. Gear down; flaps up; take-off power.



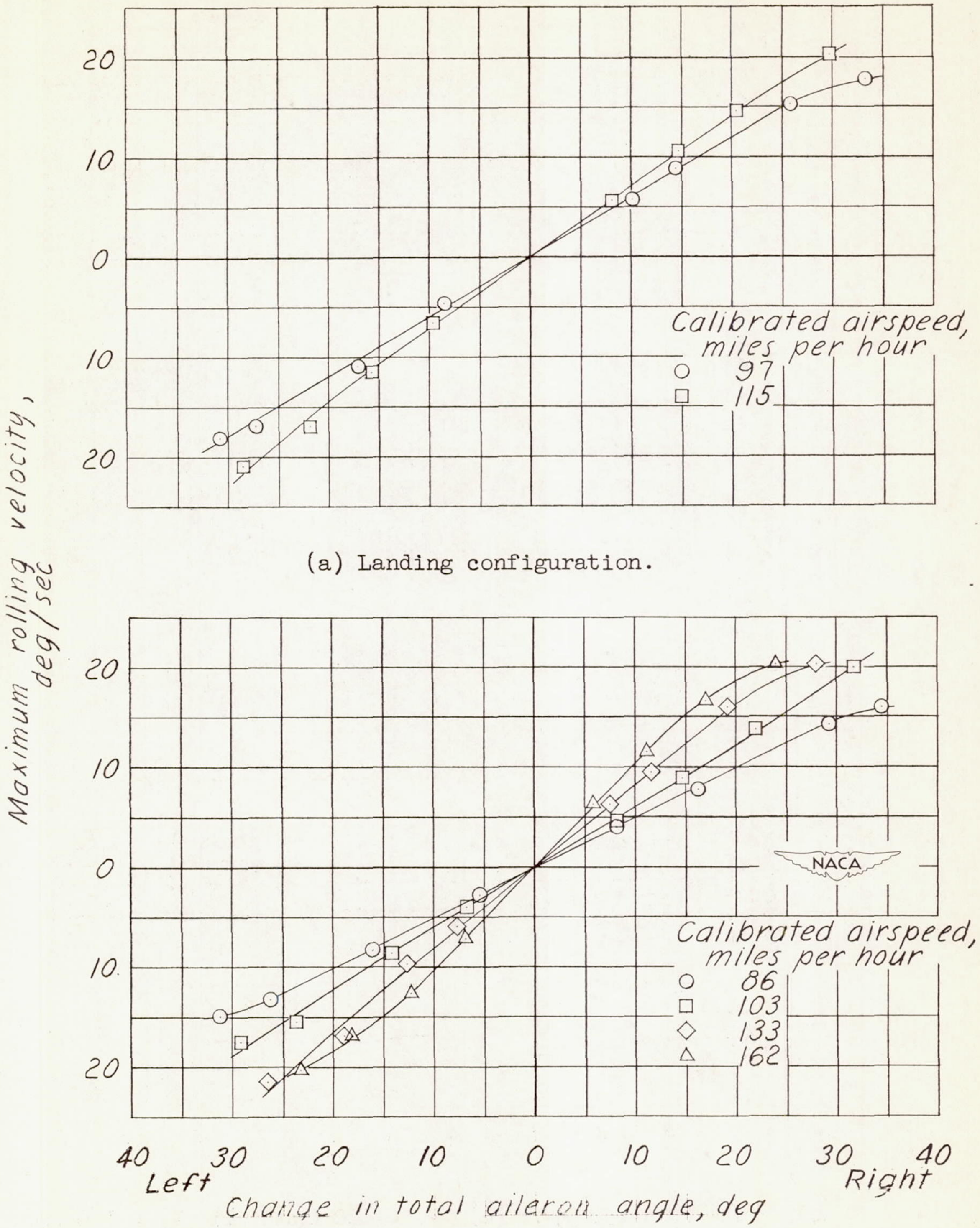
(b) Corrective control applied.

Figure 21.- Concluded.



(a) V_i = 80 mph. (b) V_i = 130 mph. (c) V_i = 100 mph. (d) V_i = 160 mph.

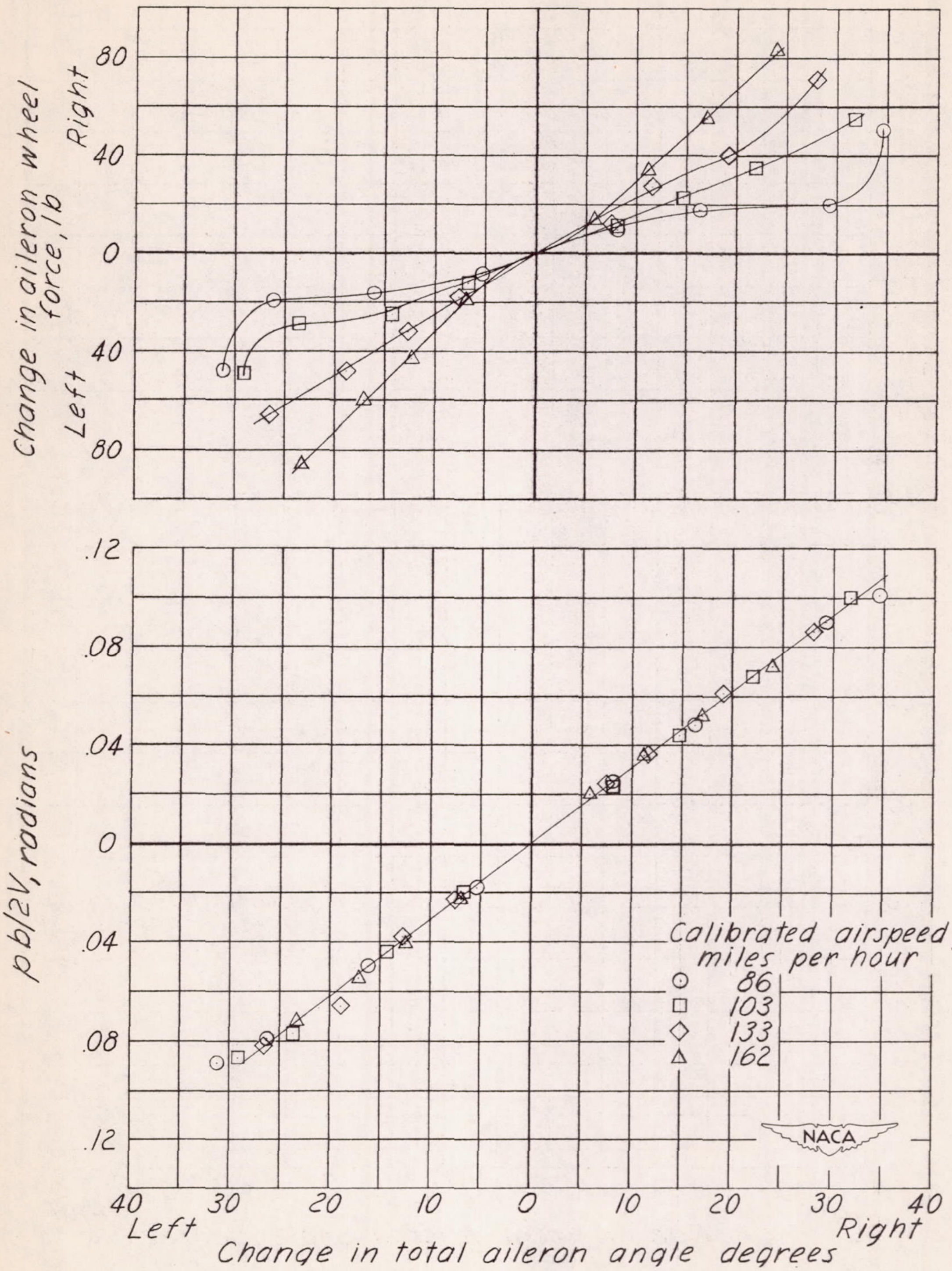
Figure 22.- Typical time histories of abrupt rudder-fixed left and right aileron rolls made with the Douglas DC-3 airplane in the clean configuration. Center-of-gravity position, 12.4 percent M.A.C.; gross weight, 24,000 pounds; altitude, 5,000 feet.



(a) Landing configuration.

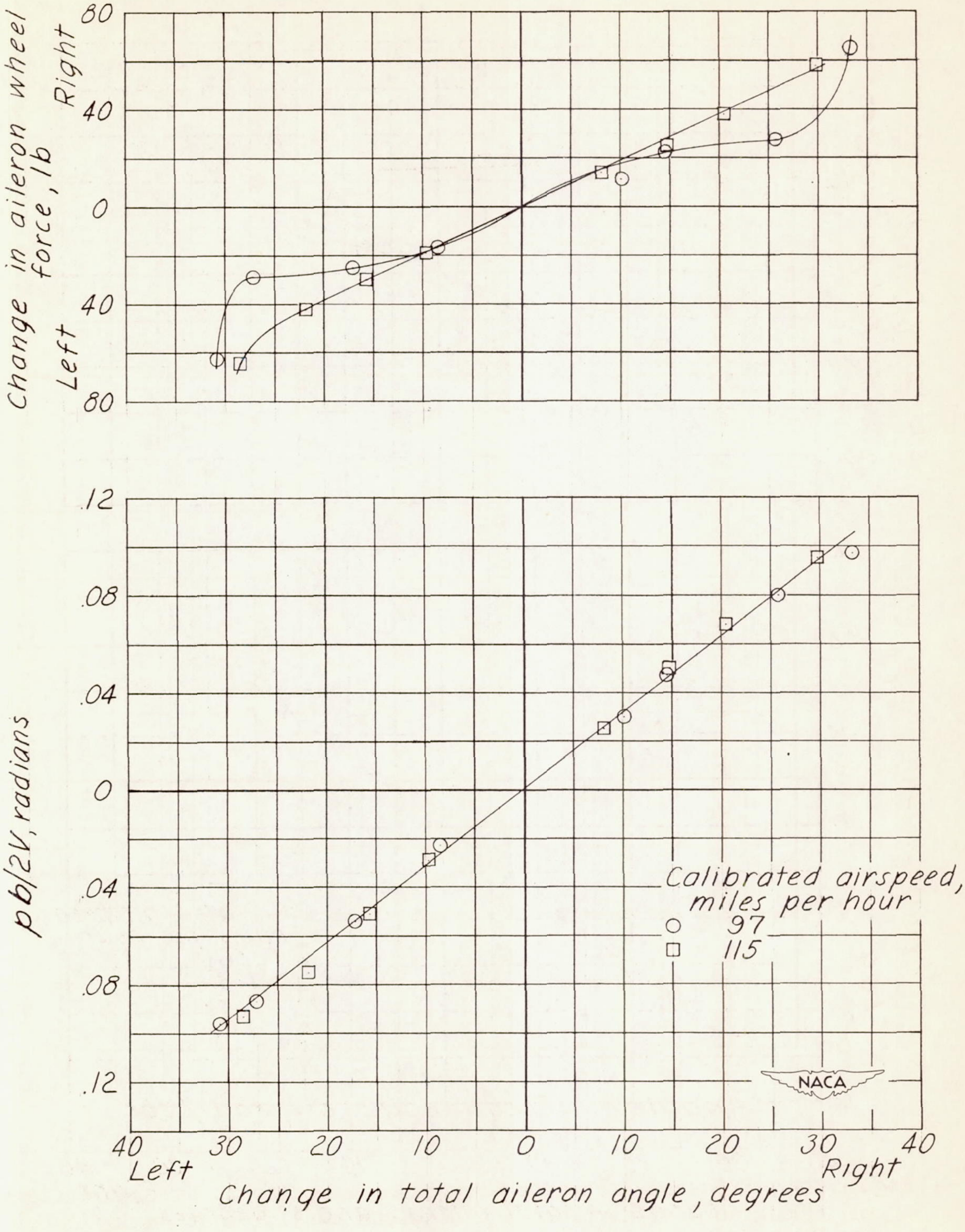
(b) Normal-rated-power clean configuration.

Figure 23.- Variation of maximum rolling velocity with total aileron angle for various conditions of the Douglas DC-3 airplane.



(a) Normal-rated-power clean configuration.

Figure 24.- Variation of aileron-effectiveness parameter and aileron wheel force with total aileron angle at various airspeeds for the Douglas DC-3 airplane.



(b) Landing configuration.

Figure 24.- Concluded.

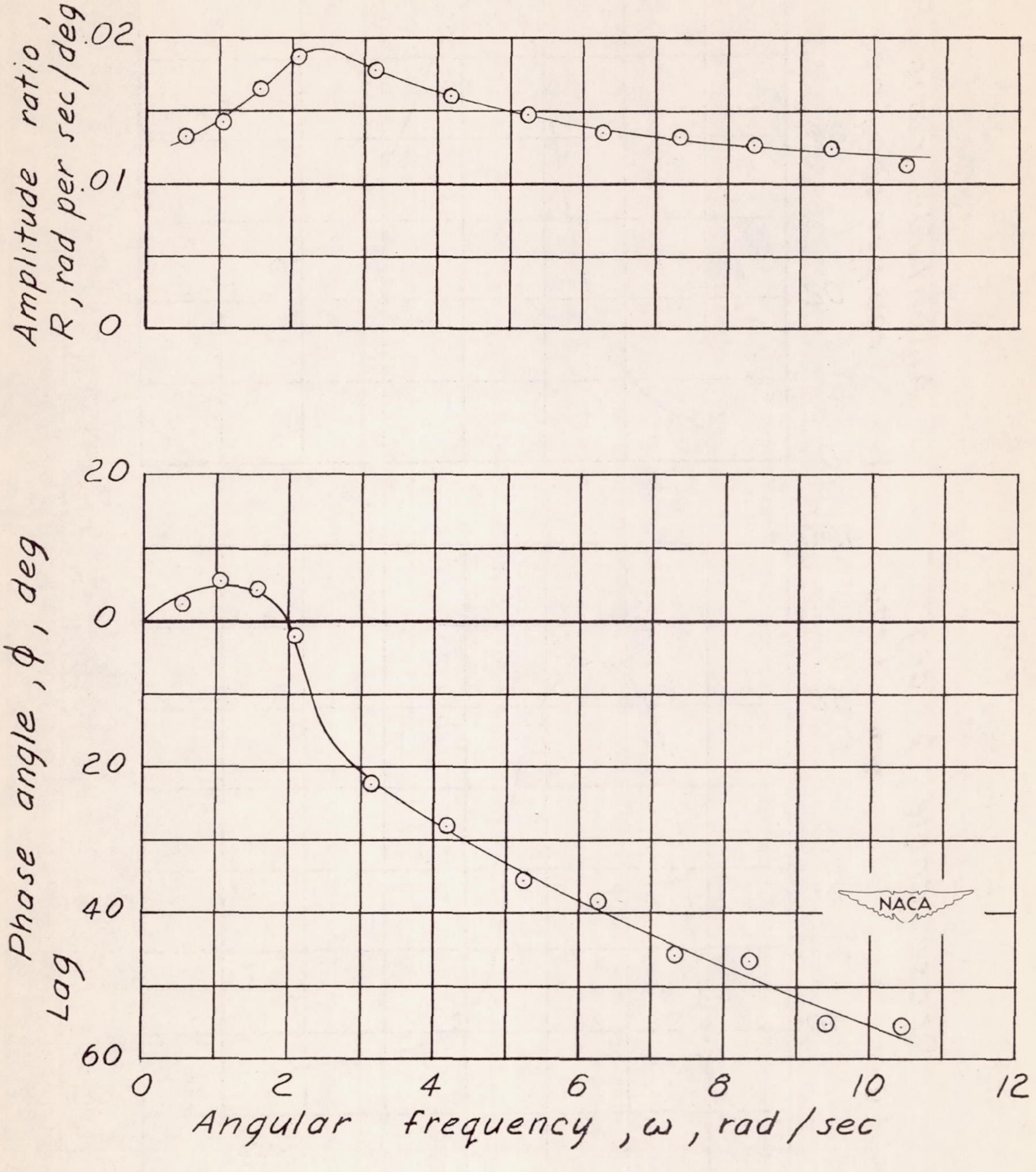


Figure 25.- Frequency response of rolling velocity to aileron deflection of a Douglas DC-3 airplane in the clean condition at an indicated airspeed of 160 mph.

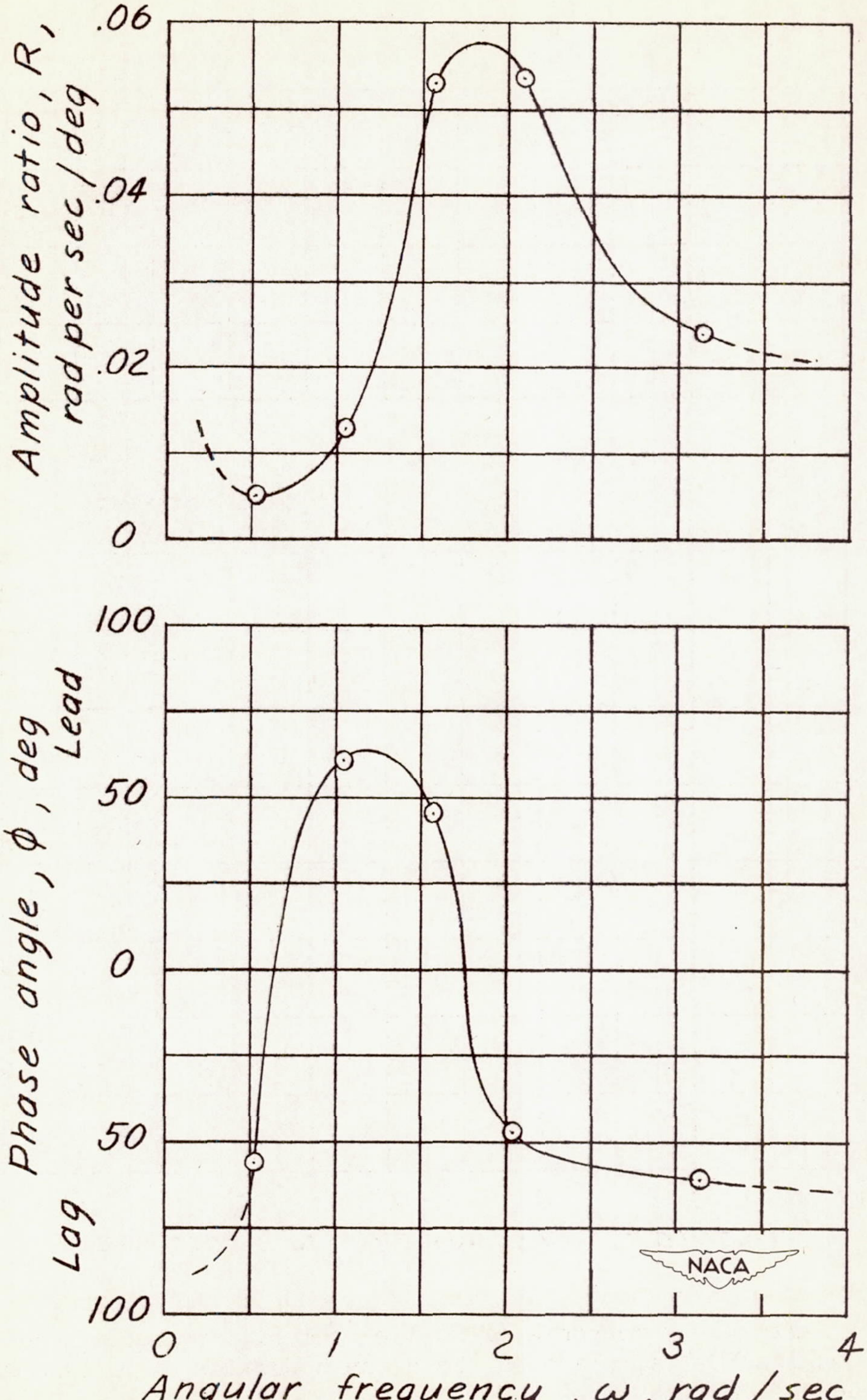
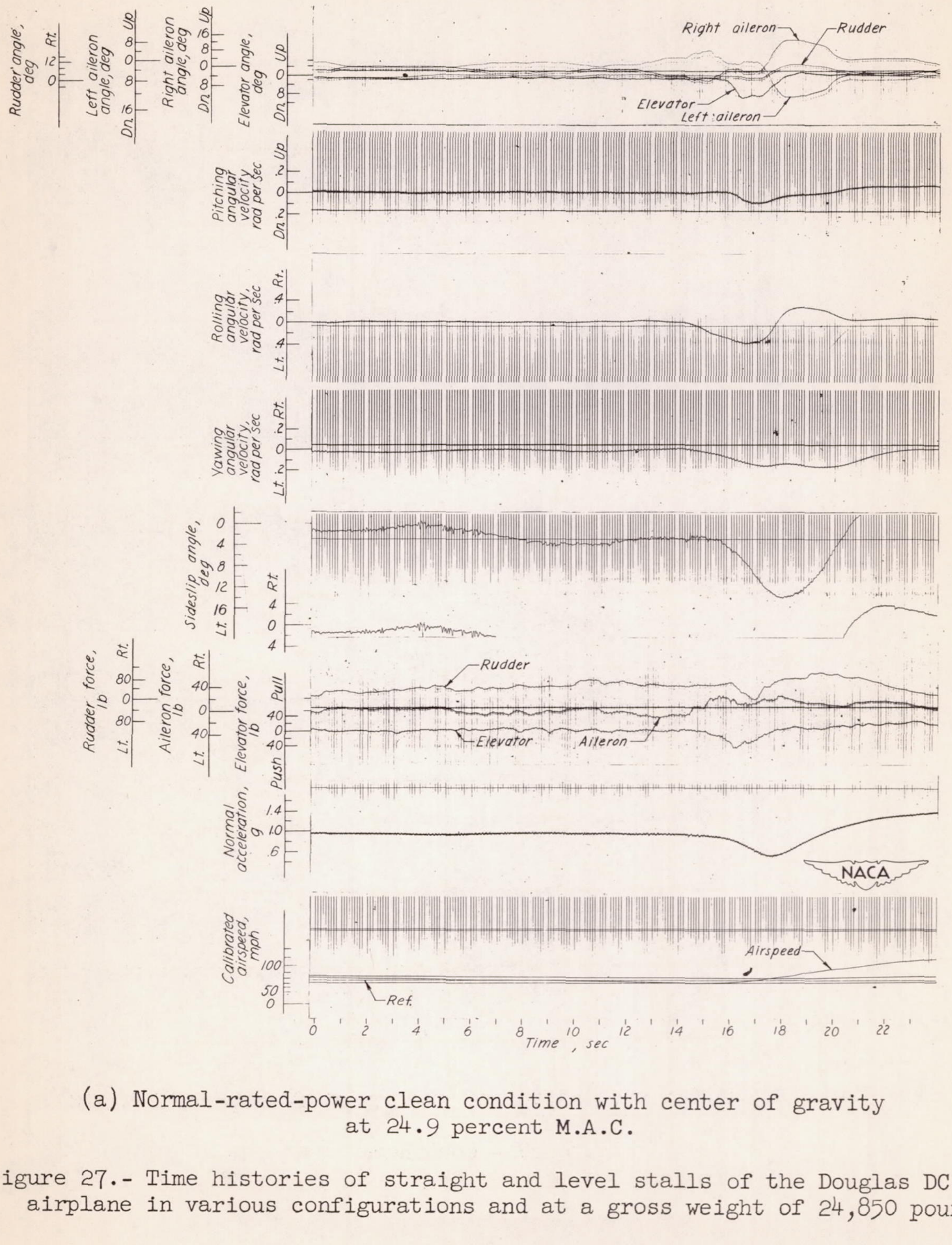
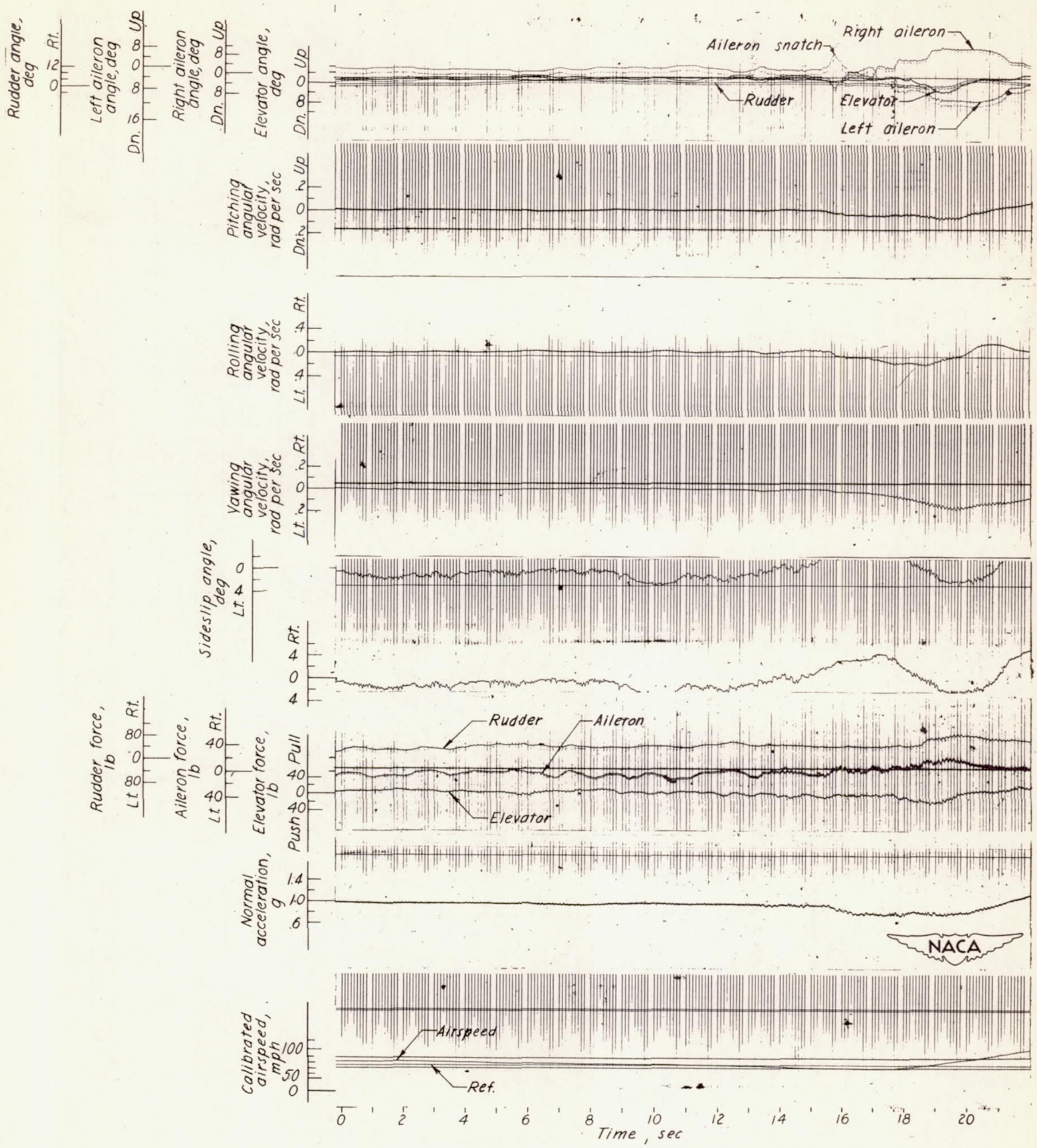


Figure 26.- Frequency response of yawing velocity to rudder deflection of a Douglas DC-3 airplane in the clean condition at an indicated airspeed of 170 mph.



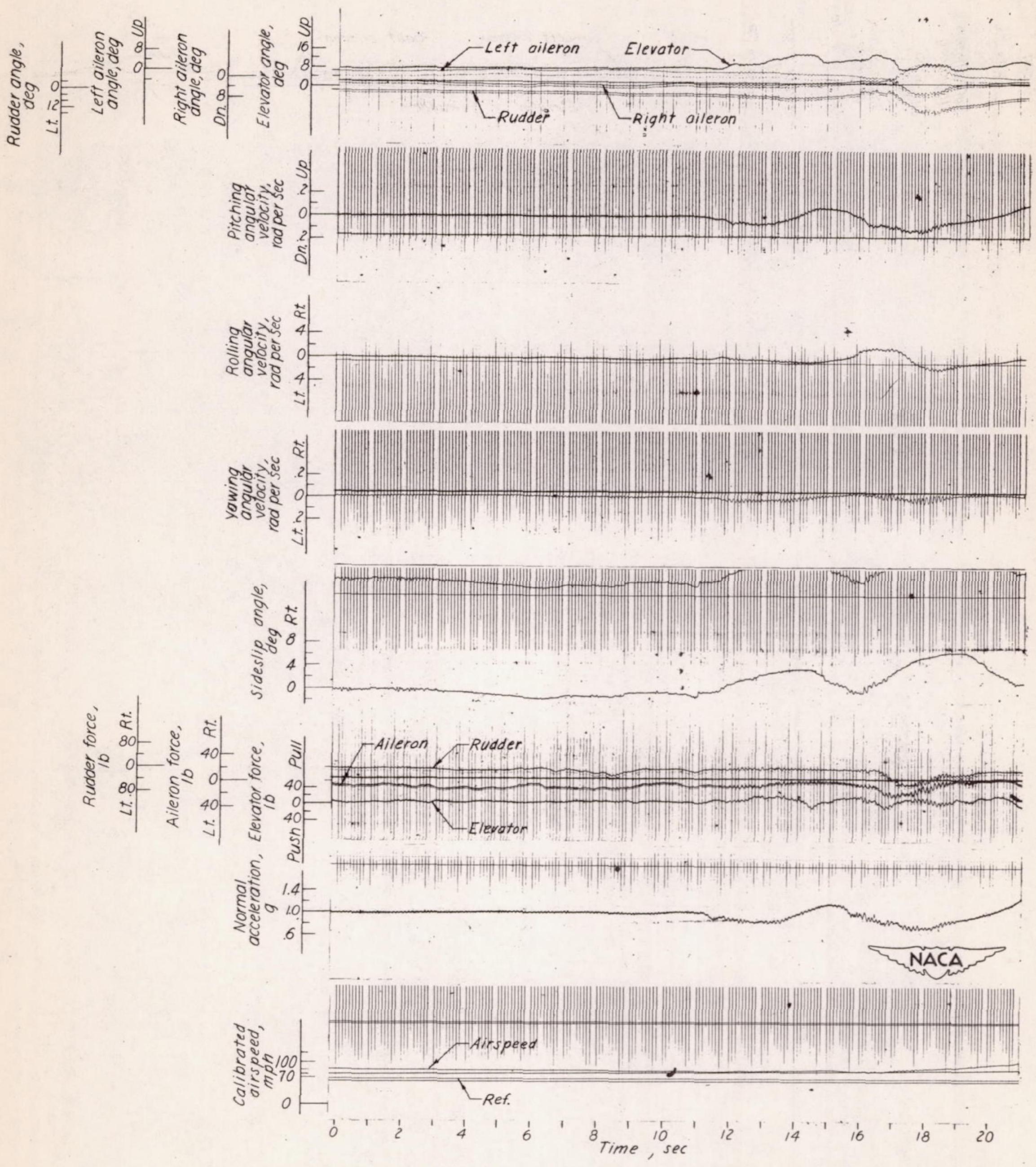
(a) Normal-rated-power clean condition with center of gravity at 24.9 percent M.A.C.

Figure 27.- Time histories of straight and level stalls of the Douglas DC-3 airplane in various configurations and at a gross weight of 24,850 pounds.



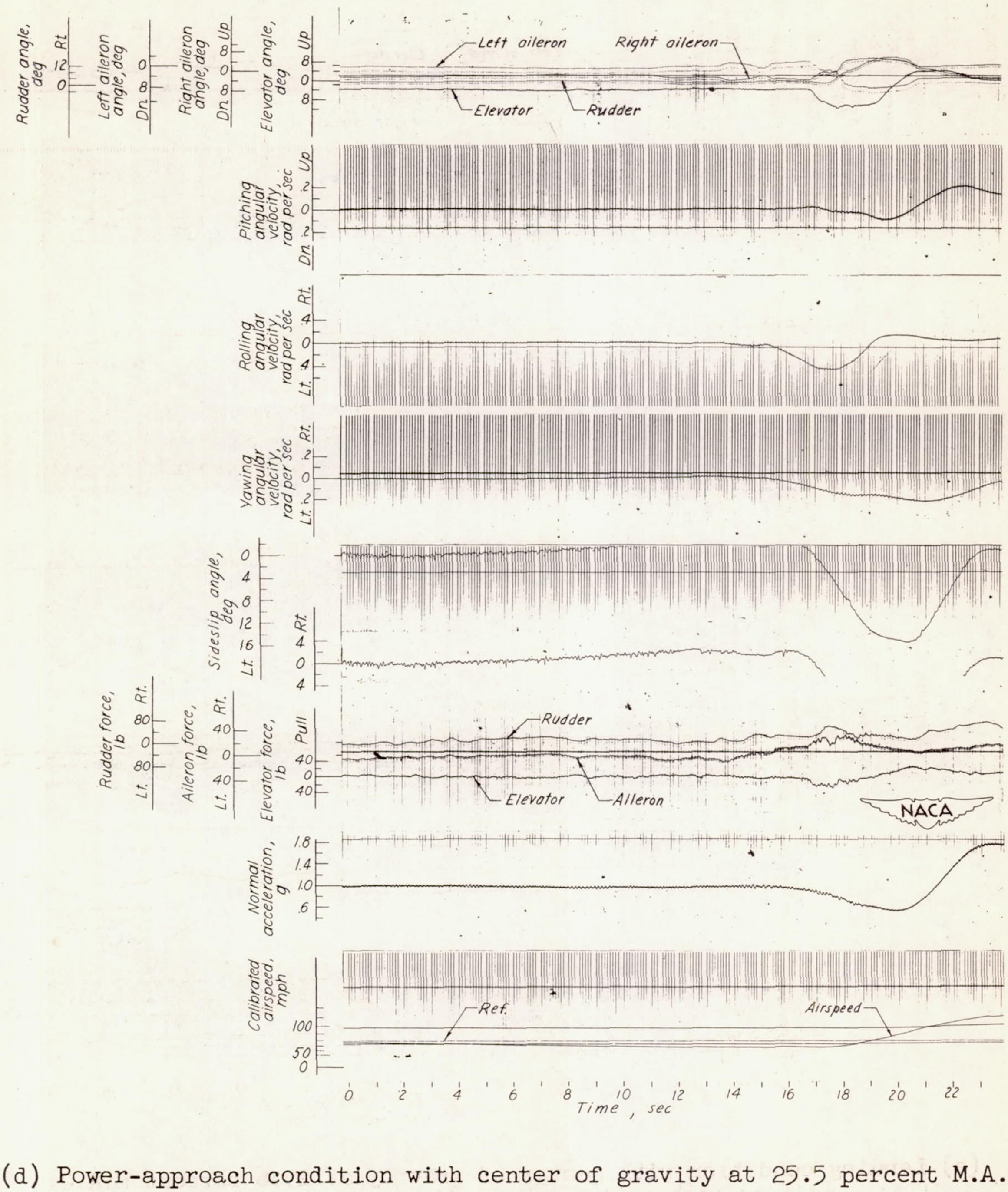
(b) Cruise condition with center of gravity at 24.8 percent M.A.C.

Figure 27.- Continued.



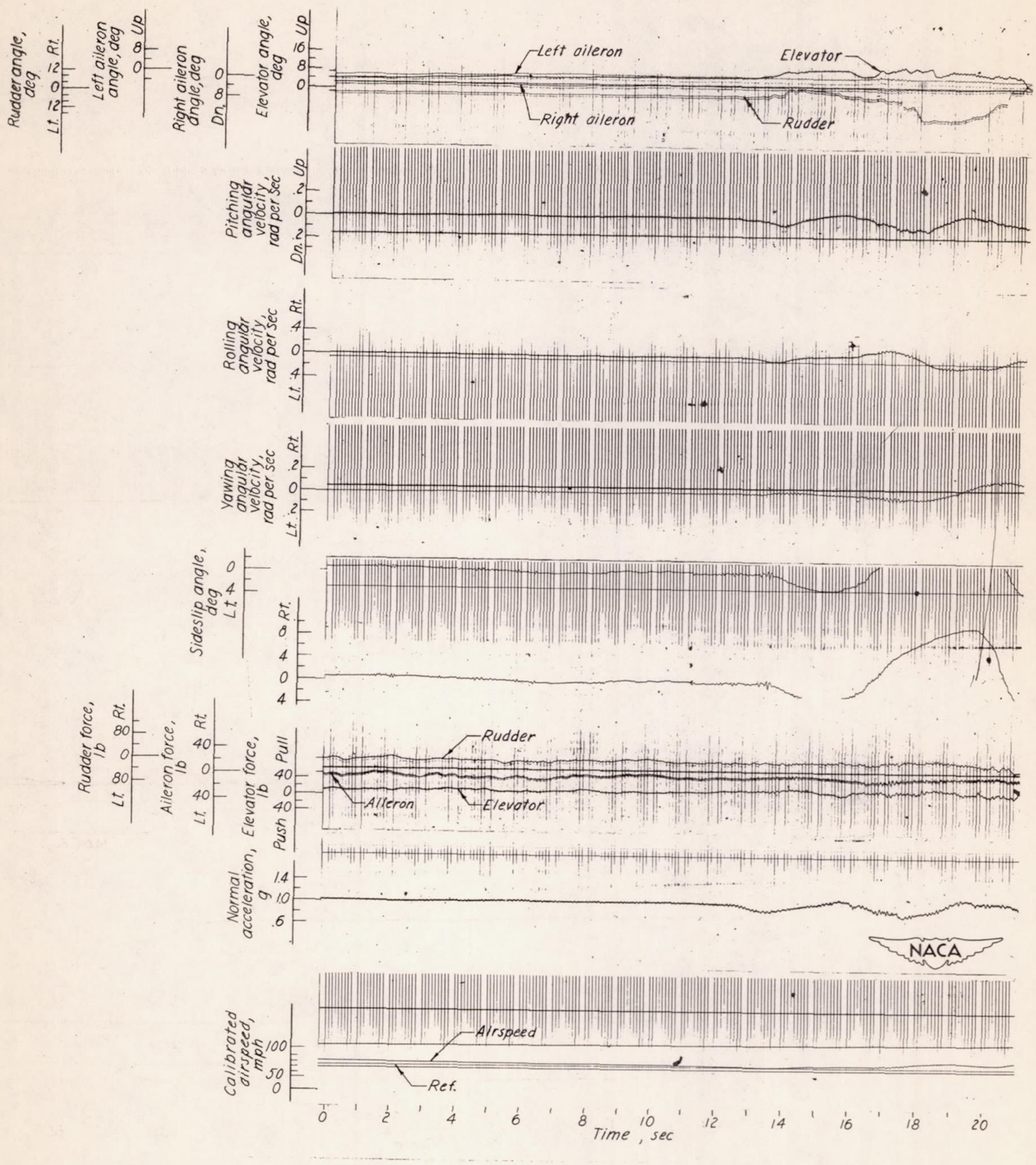
(c) Glide condition with center of gravity at 24.8 percent M.A.C.

Figure 27.- Continued.



(d) Power-approach condition with center of gravity at 25.5 percent M.A.C.

Figure 27.- Continued.



(e) Landing condition with center of gravity at 25.6 percent M.A.C.

Figure 27.- Concluded.